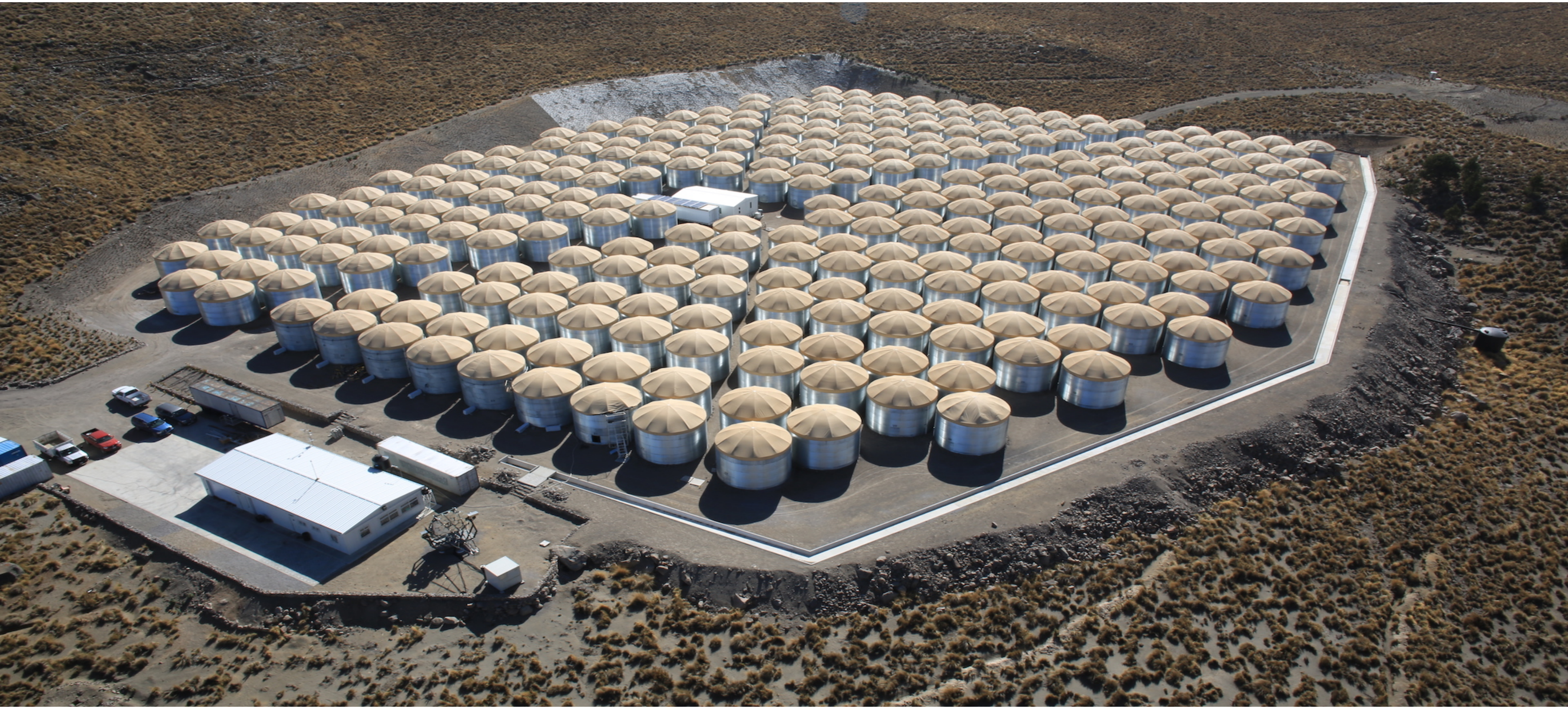
The HAWC high energy sky



Sabrina Casanova – MPIK Heidelberg - IFJ-PAN Krakow

AGILE Workshop
20-May-2016

Talk overview

Introduction:

- Extensive Air Shower Arrays

HAWC detector:

- Design, construction, performance

First Results:

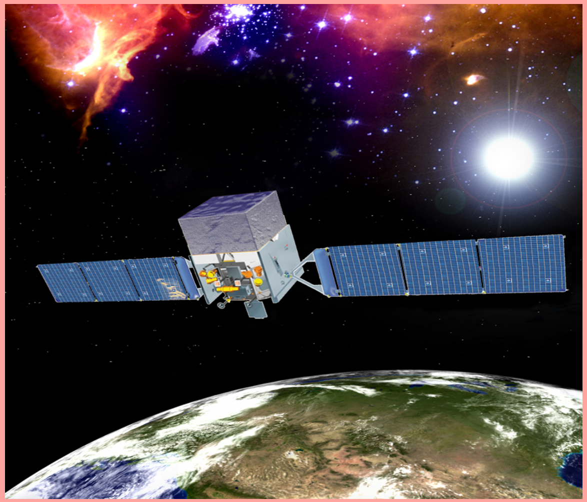
- Galactic Plane survey (new sources)
- Geminga detection
- Flaring blazars observations
- IceCube Event
- CR Anisotropy

Gamma-Ray Observatories

Wide FOV continuous operation

TeV sensitivity

Satellites



AGILE
EGRET
Fermi-LAT

EAS

Milagro
Tibet ASγ
ARGO-YBJ
HAWC

IACT

H.E.S.S.
MAGIC
VERITAS
CTA

Space-based

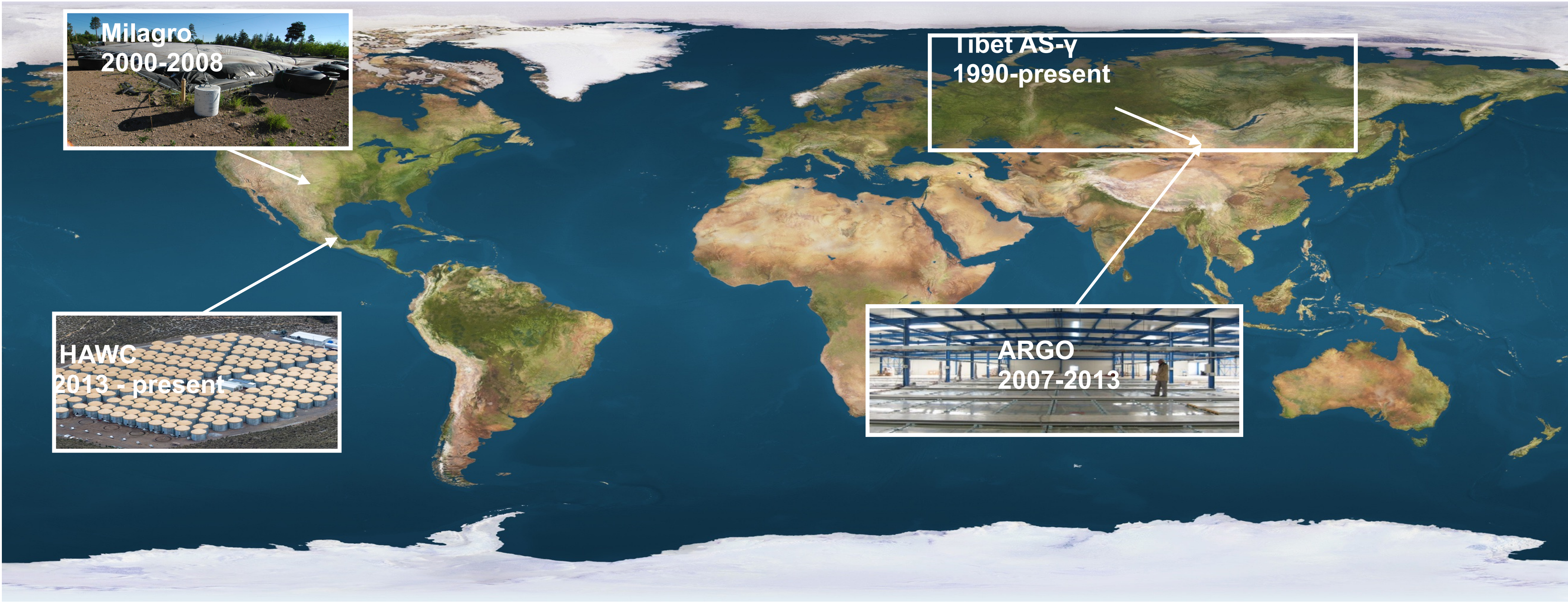
Ground-based

EAS Detectors

- Main features:
  - Large active area $>10^4$ m^2.
  - High duty cycle >90%.
  - Large FOV (~2sr).

WHAT CAN WE DO WITH EAS ?

- Highest energy gamma-rays (>10 TeV)
- Continuous observation: Transient phenomena and flaring sources (e.g. GRBs, AGNs). Long duration light curves and multi-wavelength follow-up.
- Large gamma-ray structures: extended sources, Galactic Plane emission, Fermi bubbles, surveys
- Cosmic ray physics.



HAWC Collaboration

USA:
Pennsylvania State University
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University
Michigan State University
University of Rochester
University of California Santa Cruz

Mexico:
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

Poland:
Instytut Fizyki Jądrowej im. Henryka Niewodniczańskiego - Polskiej Akademii Nauk

Germany:
Max-Planck-Institut für Kernphysik

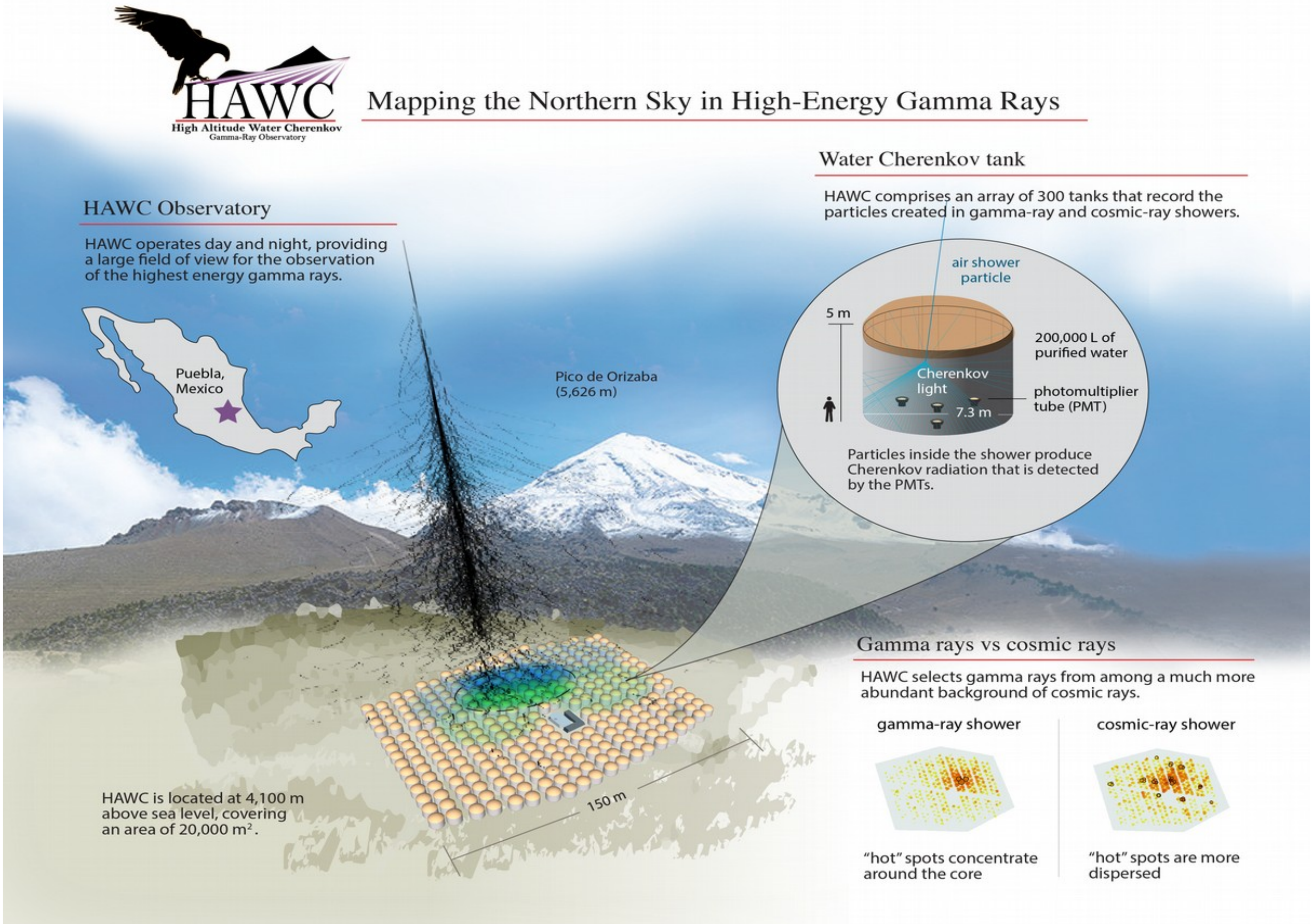
HAWC Milestones

- Feb, 2011: Beginning of the construction.
- Summer 2011: VAMOS engineering array (7 tanks).
- October 2012: 30 tanks, first results.
- August 2013: beginning of science operations.
- March, 2015: Detector inauguration.
- April, 2016: First year catalog.

High Altitude Water Cherenkov Detector

- 4100 meter site in Mexico
- 22,000 m^2 detector area.
- 300 4.5m high, 7.3m diameter Water Cherenkov Detectors
- 100 GeV - 100 TeV Sensitivity
- Average Angular Resolution (68% Cont.) 0.5°.
- Strengths:
  - Wide field-of-view
  - Extreme high-energy reach

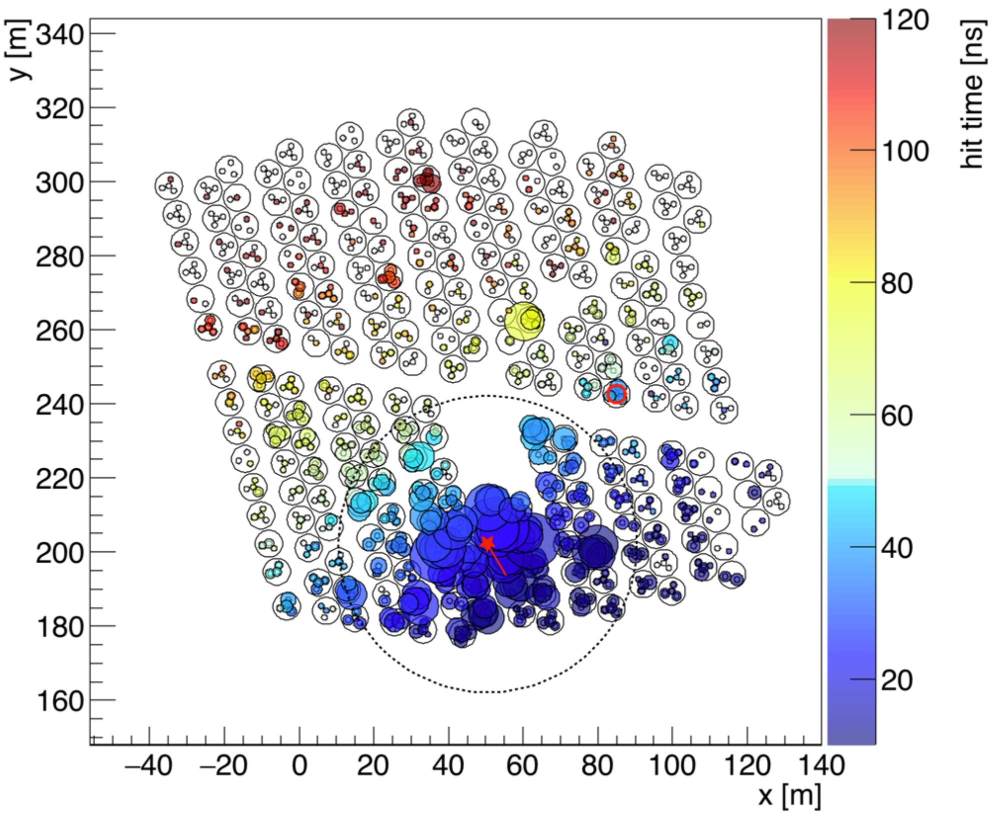
- Main Background: Hadronic cosmic rays
  - Crab Nebula: 400 photons/day
  - Background: 15000 cosmic rays/second


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory
Mapping the Northern Sky in High-Energy Gamma Rays
HAWC Observatory
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.
Puebla, Mexico
Pico de Orizaba (5,626 m)
Water Cherenkov tank
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.
air shower particle
5 m
200,000 L of purified water
Cherenkov light
photomultiplier tube (PMT)
7.3 m
Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.
Gamma rays vs cosmic rays
HAWC selects gamma rays from among a much more abundant background of cosmic rays.
gamma-ray shower
cosmic-ray shower
"hot" spots concentrate around the core
"hot" spots are more dispersed
HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².
150 m

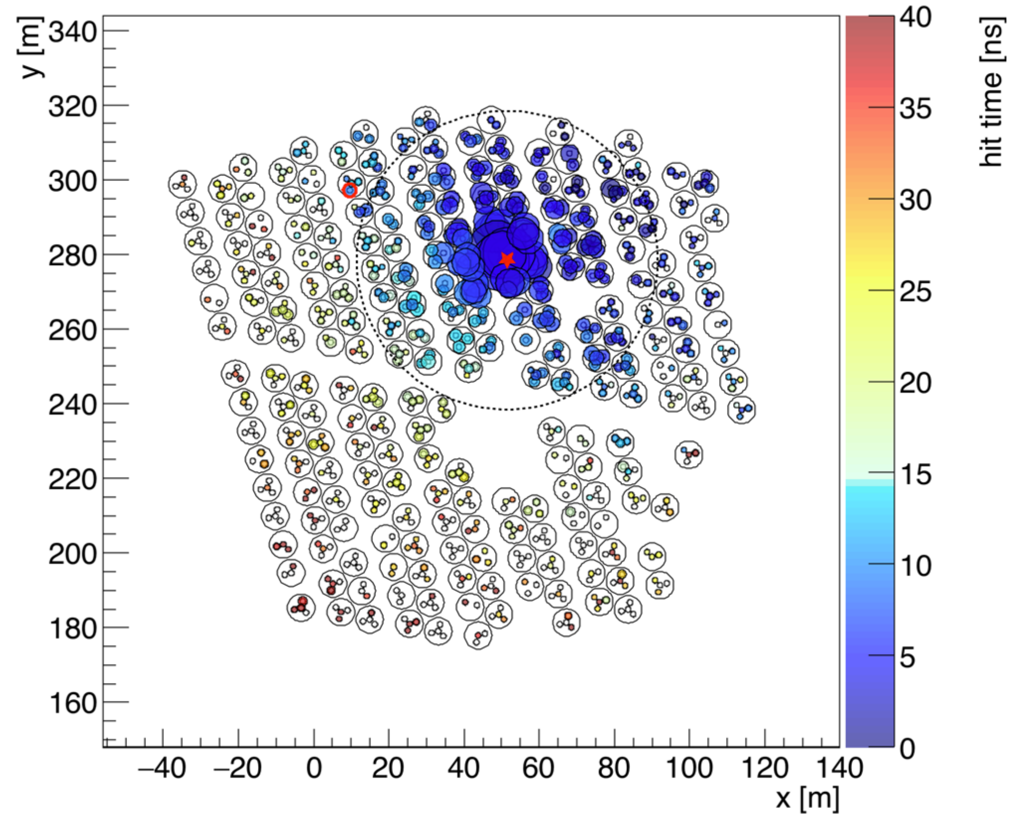
Gamma/Hadron Separation

- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- In gamma-ray showers, most of the signal at ground level is located near the shower axis.
- In charged cosmic rays tend to "break apart", much messier signals at ground level.

HAWC Data – Hadron Shower

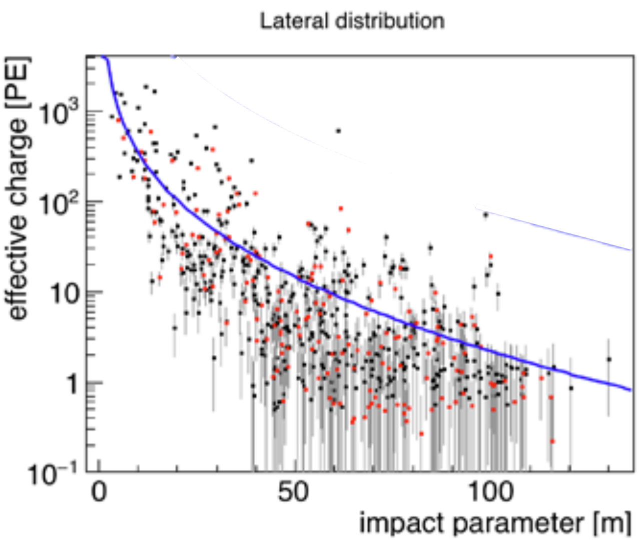


HAWC Data – Likely Gamma Ray

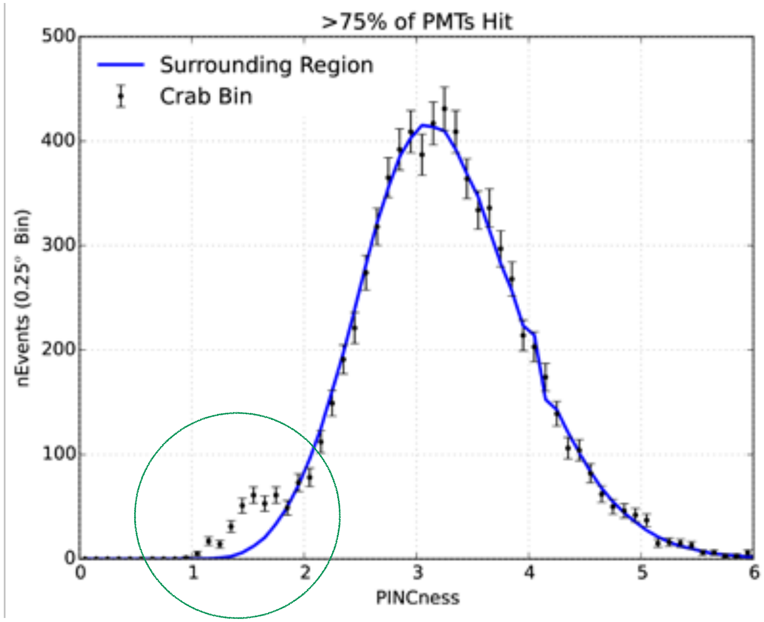


Gamma/Hadron Separation

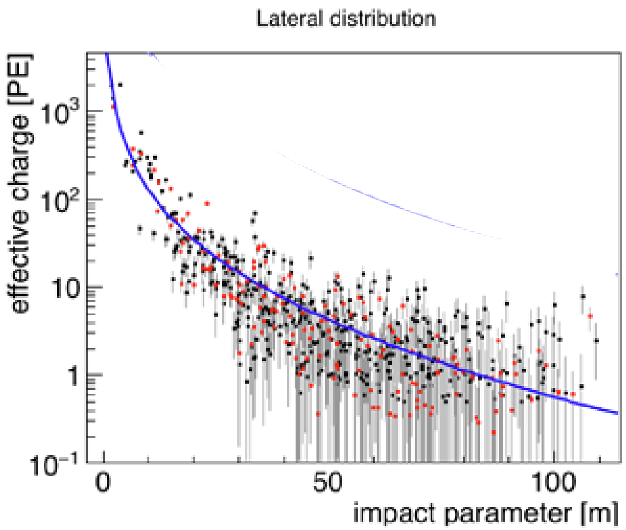
hadronic event



gamma/hadron parameter



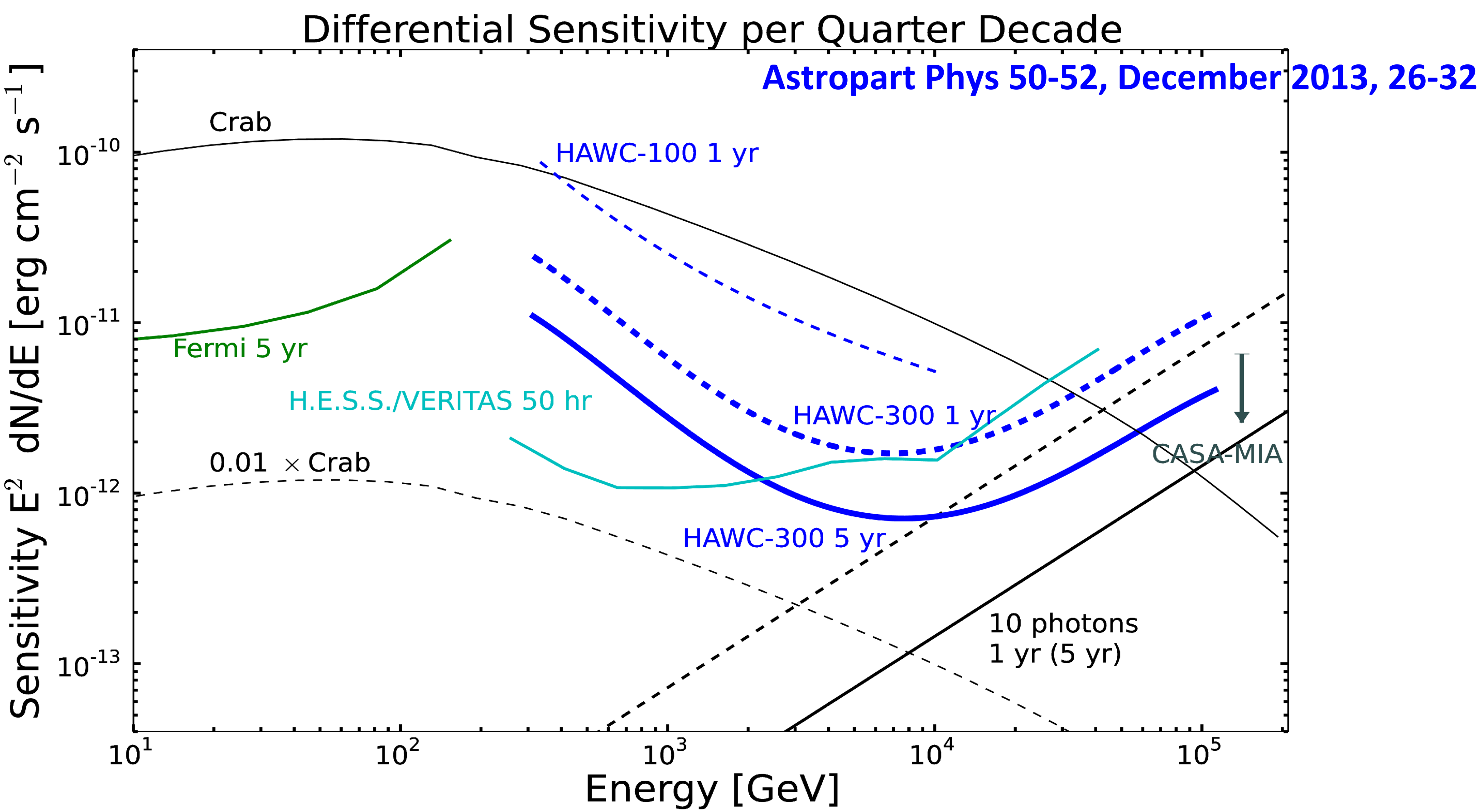
gamma ray-like event



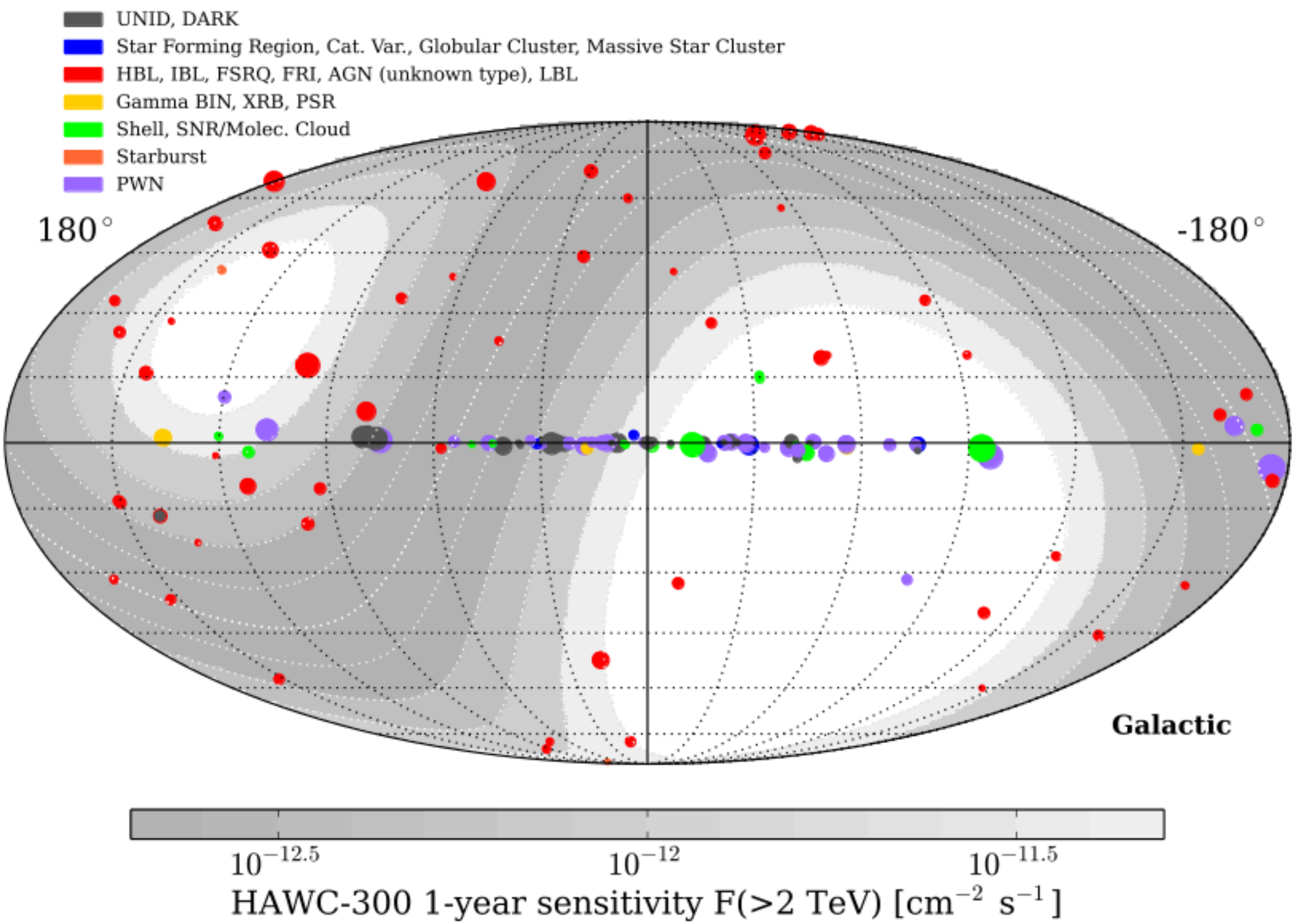
- We compute the distribution *PINCness* for a region around the Crab.
- Scale the "background" region to the same solid angle as the bin around the Crab.
- Only events with >75% of PMTs hit were used

HAWC Sensitivity

- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs. Survey > half sky to 40 mCrab [5σ] (1yr) and < 20mCrab [5σ] (5yr)

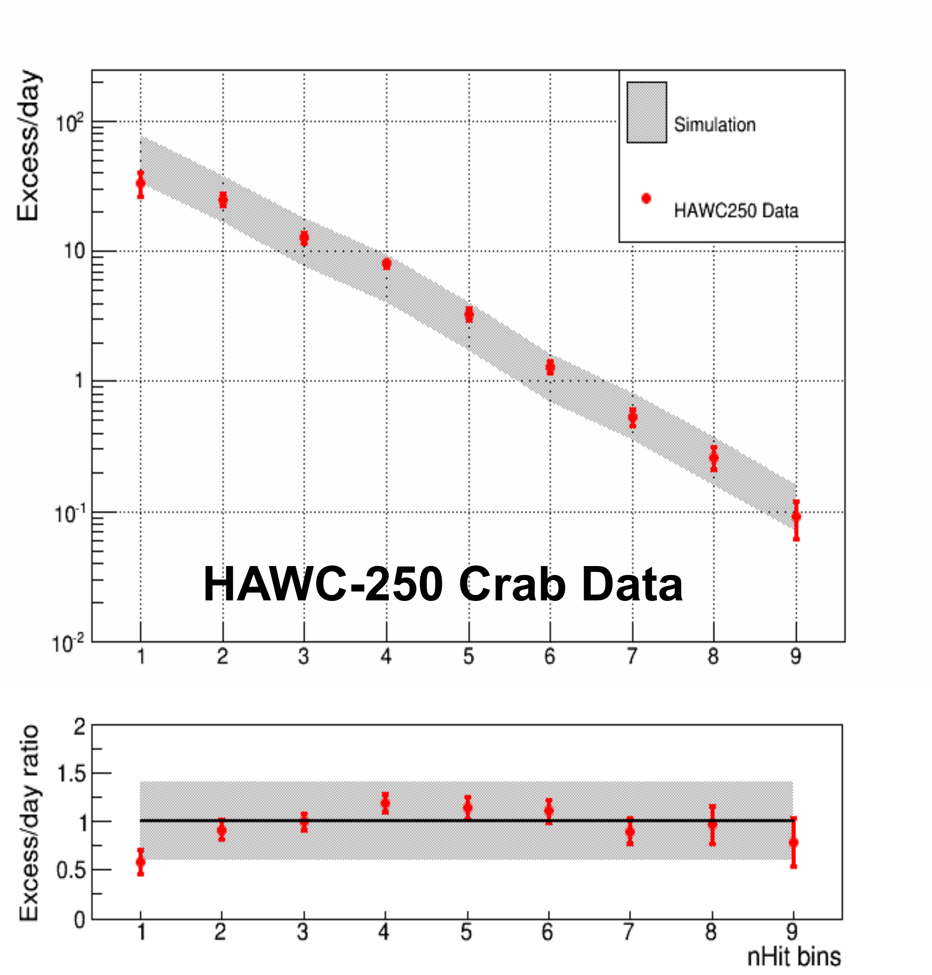


HAWC FOV


UNID, DARK
Star Forming Region, Cat. Var., Globular Cluster, Massive Star Cluster
HBL, IBL, FSRQ, FRI, AGN (unknown type), LBL
Gamma BIN, XRB, PSR
Shell, SNR/Molec. Cloud
Starburst
PWN
180°
-180°
Galactic
$10^{-12.5}$
10^{-12}
$10^{-11.5}$
HAWC-300 1-year sensitivity F(>2 TeV) [cm^{-2} s^{-1}]

Crab Nebula: Performance Benchmark

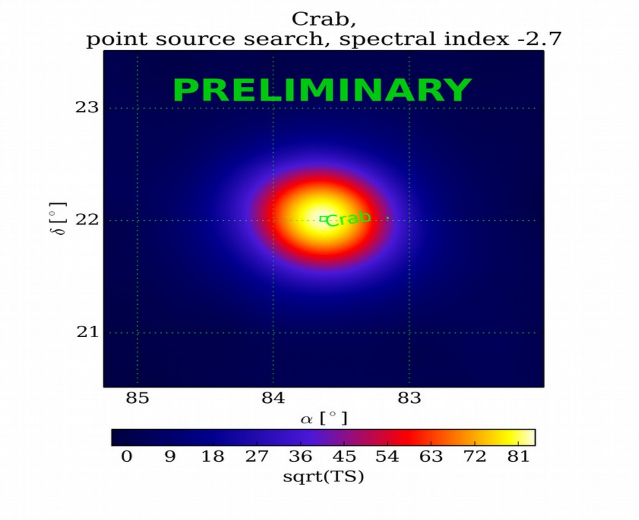
Salesa Greus, ICRC 2015

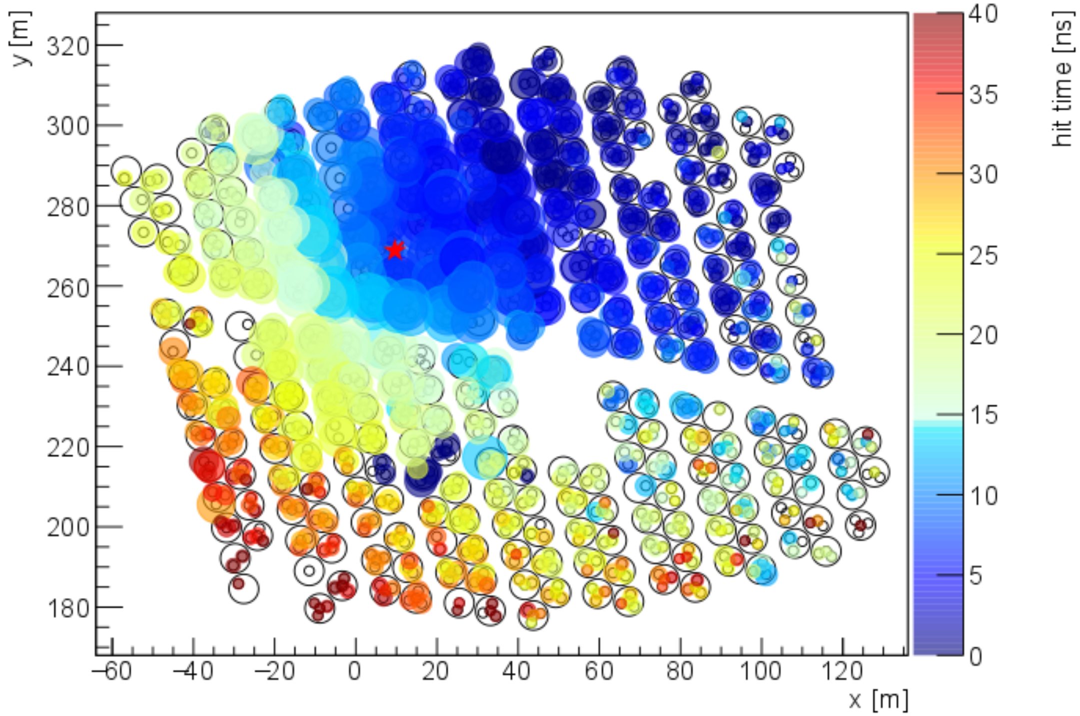


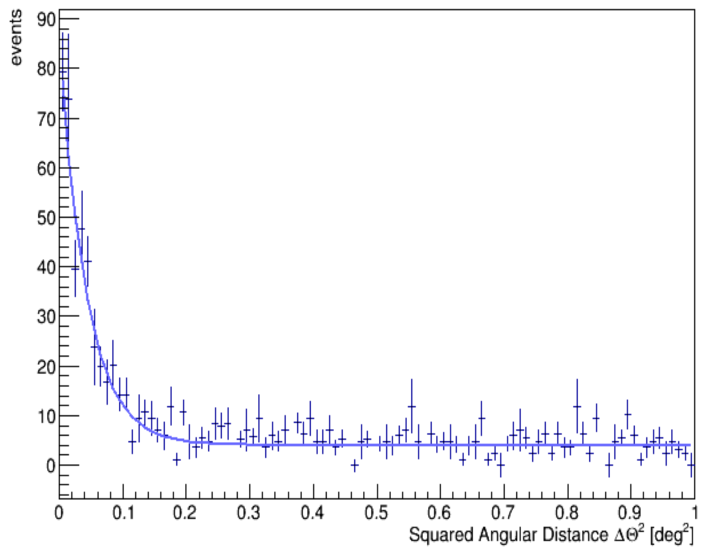
Seeing the Right Number of Gamma Rays…

The Crab Nebula

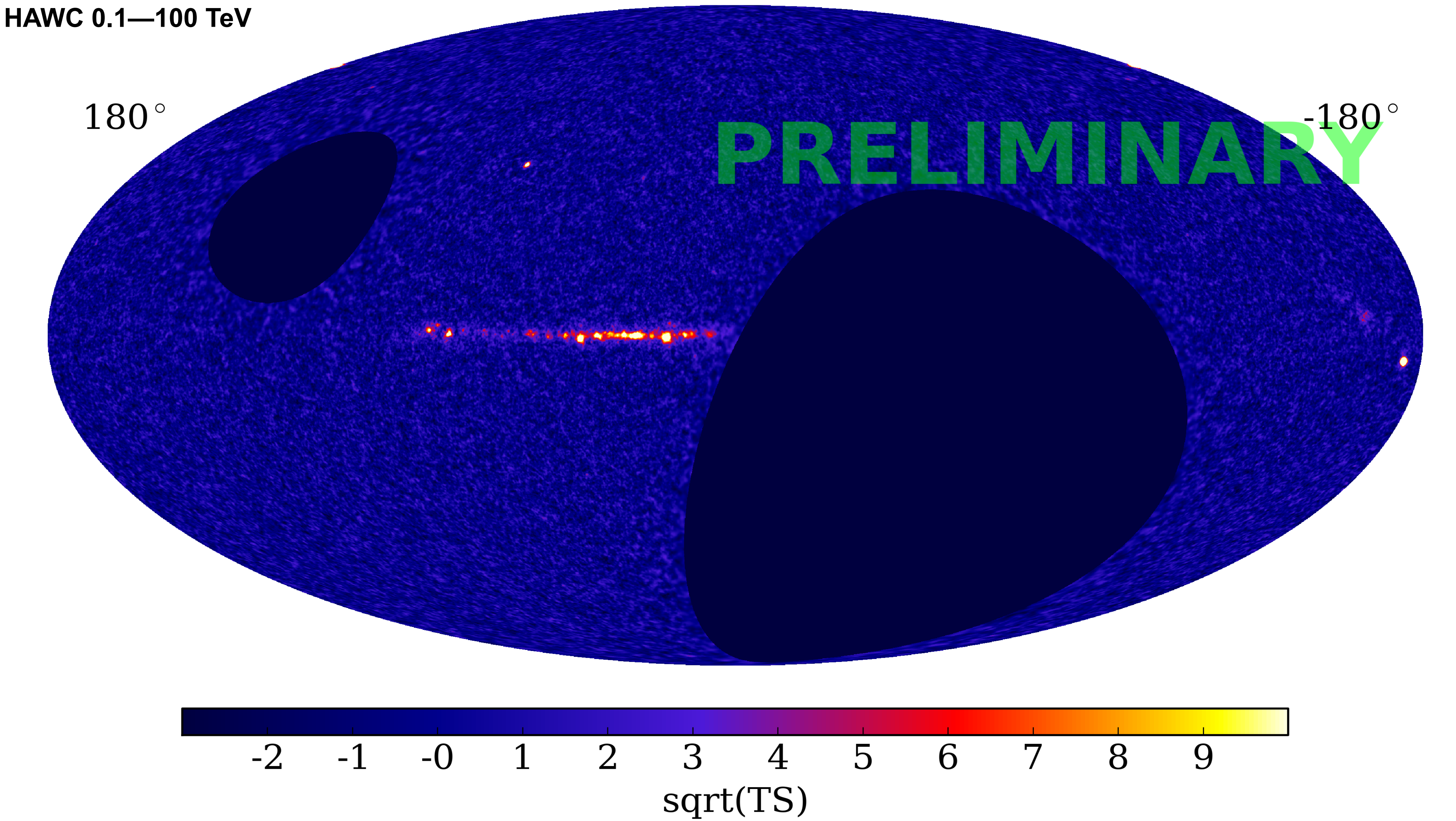
- Crab Nebula detected with high significance ~85σ in 1 yr.
- Gamma-like event of ~ 60TeV within 0.25 deg from the Crab position.
- It was used to test our angular resolution and g/h cuts.



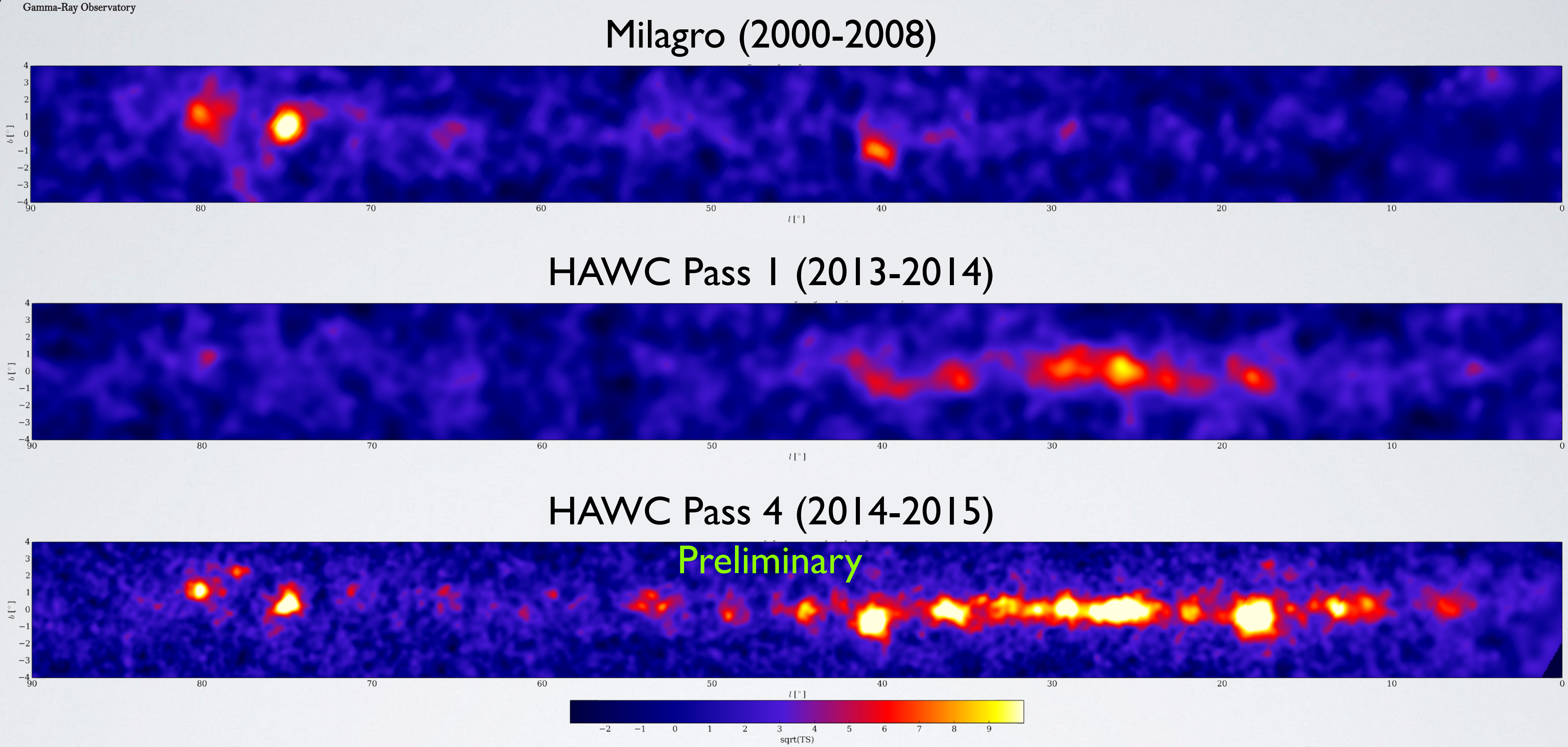




HAWC SkyMap 340 Days

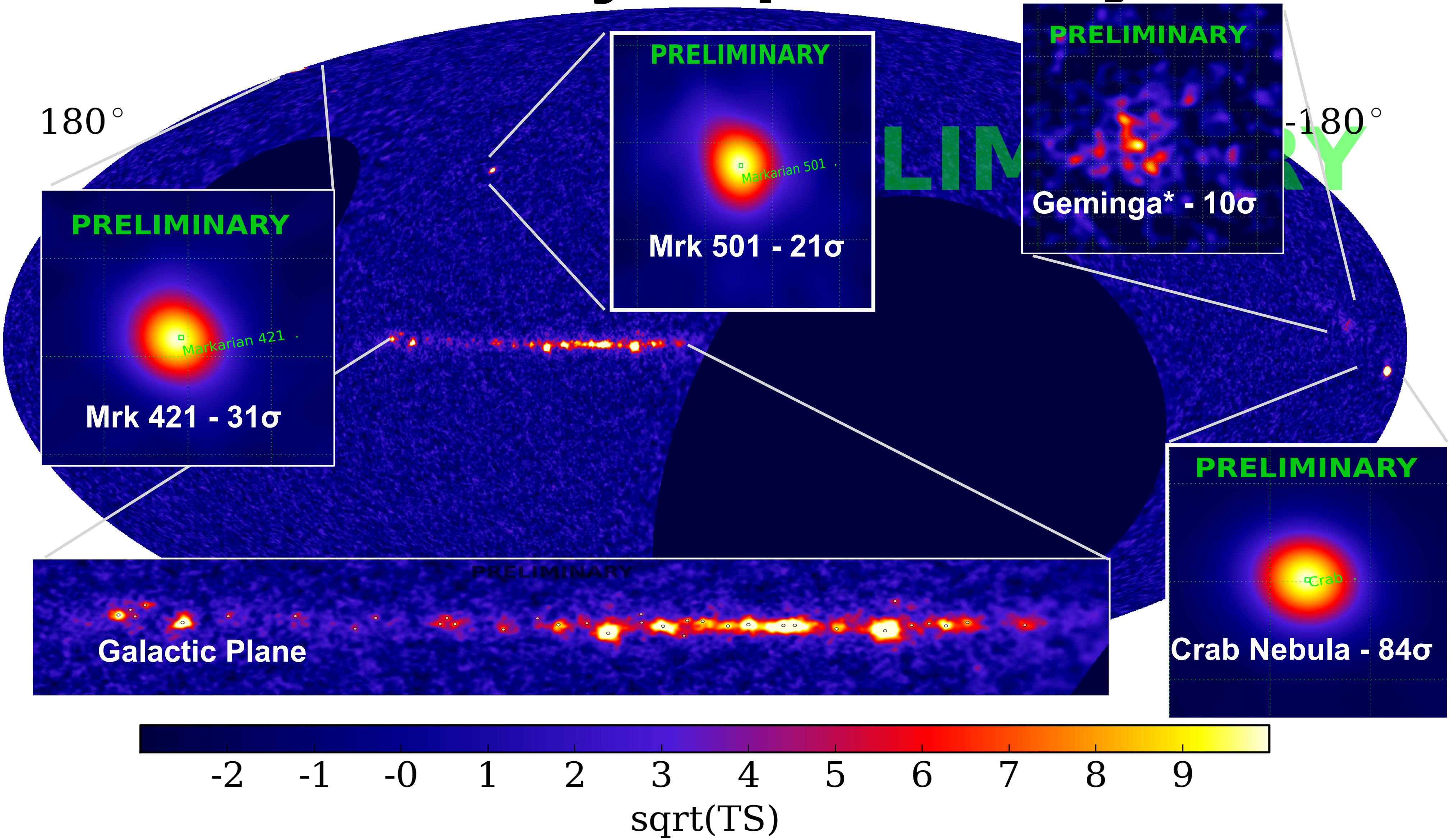


Galactic Plane

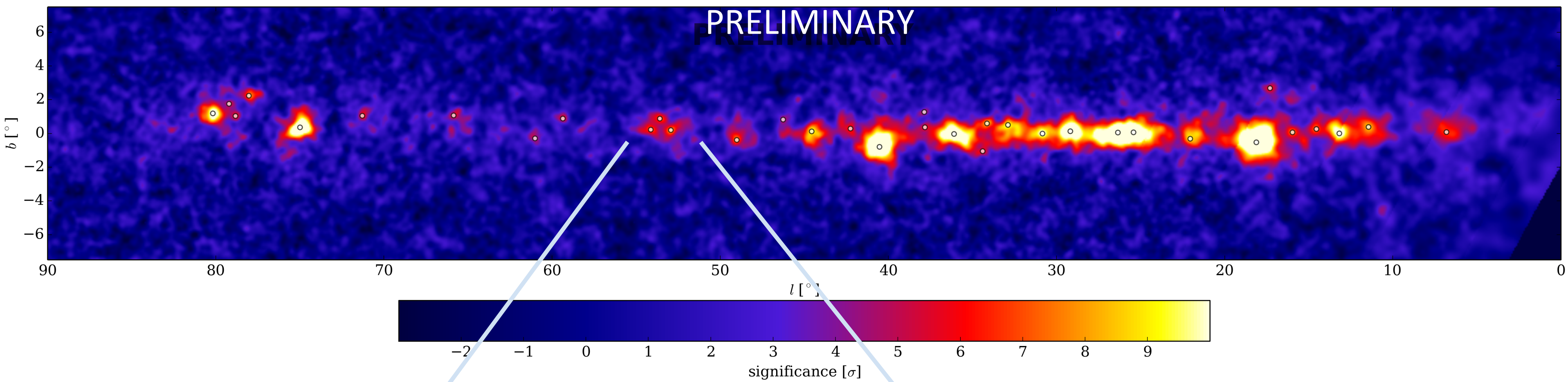


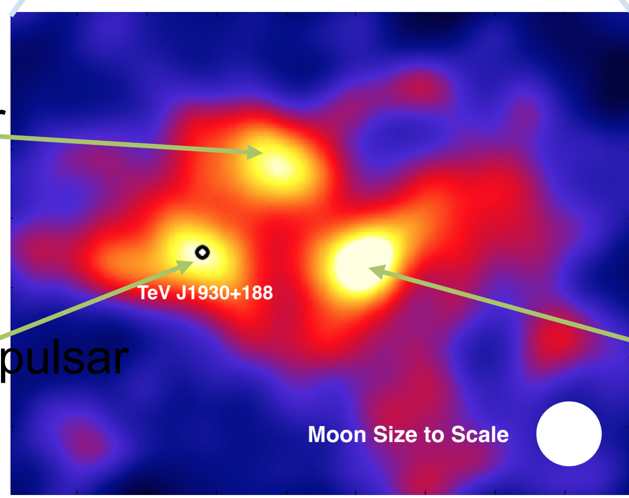
HAWC is about 15 more sensitive with lower energy threshold and more sensitive towards Galactic centre (HAWC is located more south with respect to Milagro) .

HAWC SkyMap 340 Days



HAWC View of the Galactic Plane





New: Association unclear

SNR with very energetic pulsar

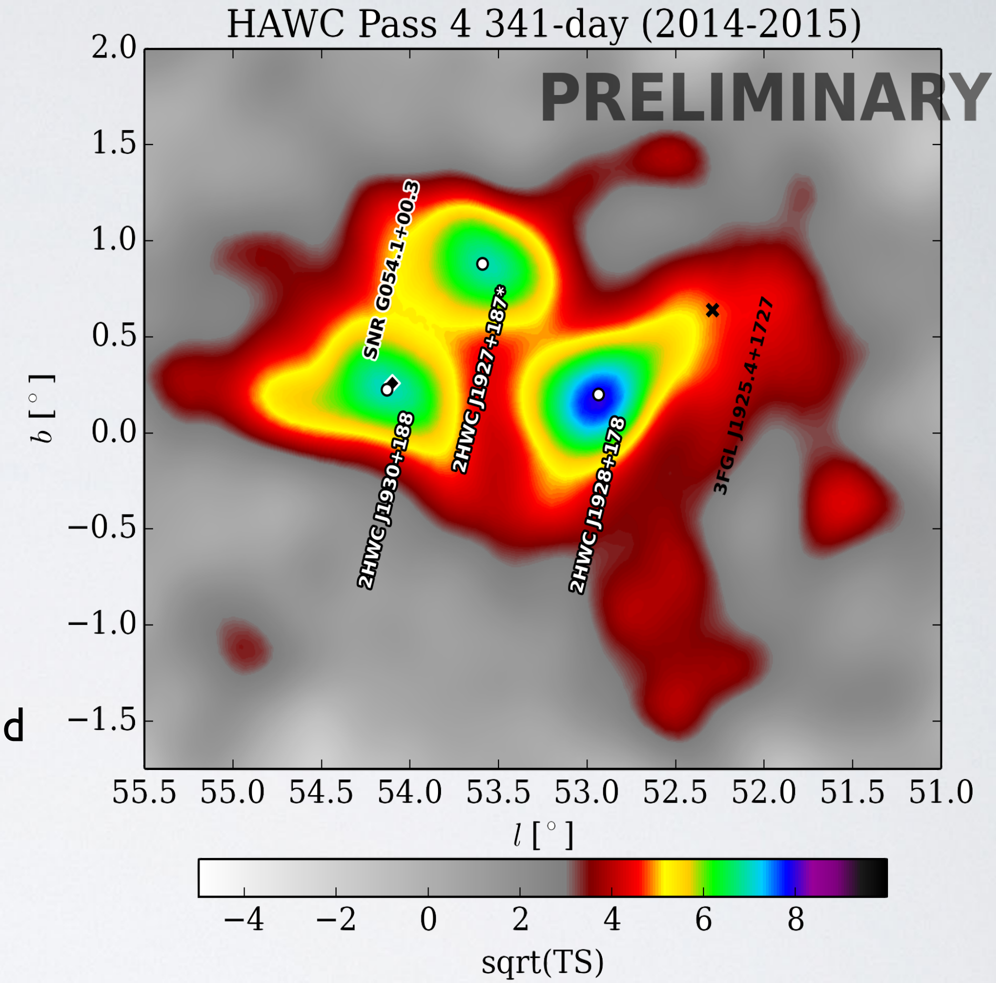
New: Pulsar ~8kpc (26,000 ly) away

~40 sources seen in first year
25% are new!

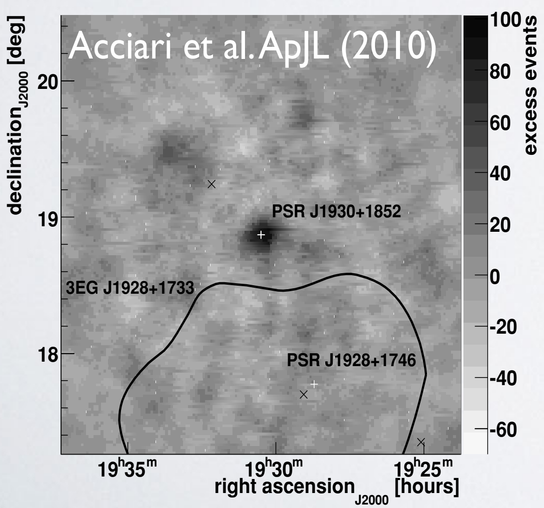
Paper in preparation!

New TeV Sources!

New TeV emission region
2HWC J1927+187*
- ~7σ pre-trials
- current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology



2HWC J1930+188
- coincident with VER J1930+188 (SNR G54.1+00.3 / PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

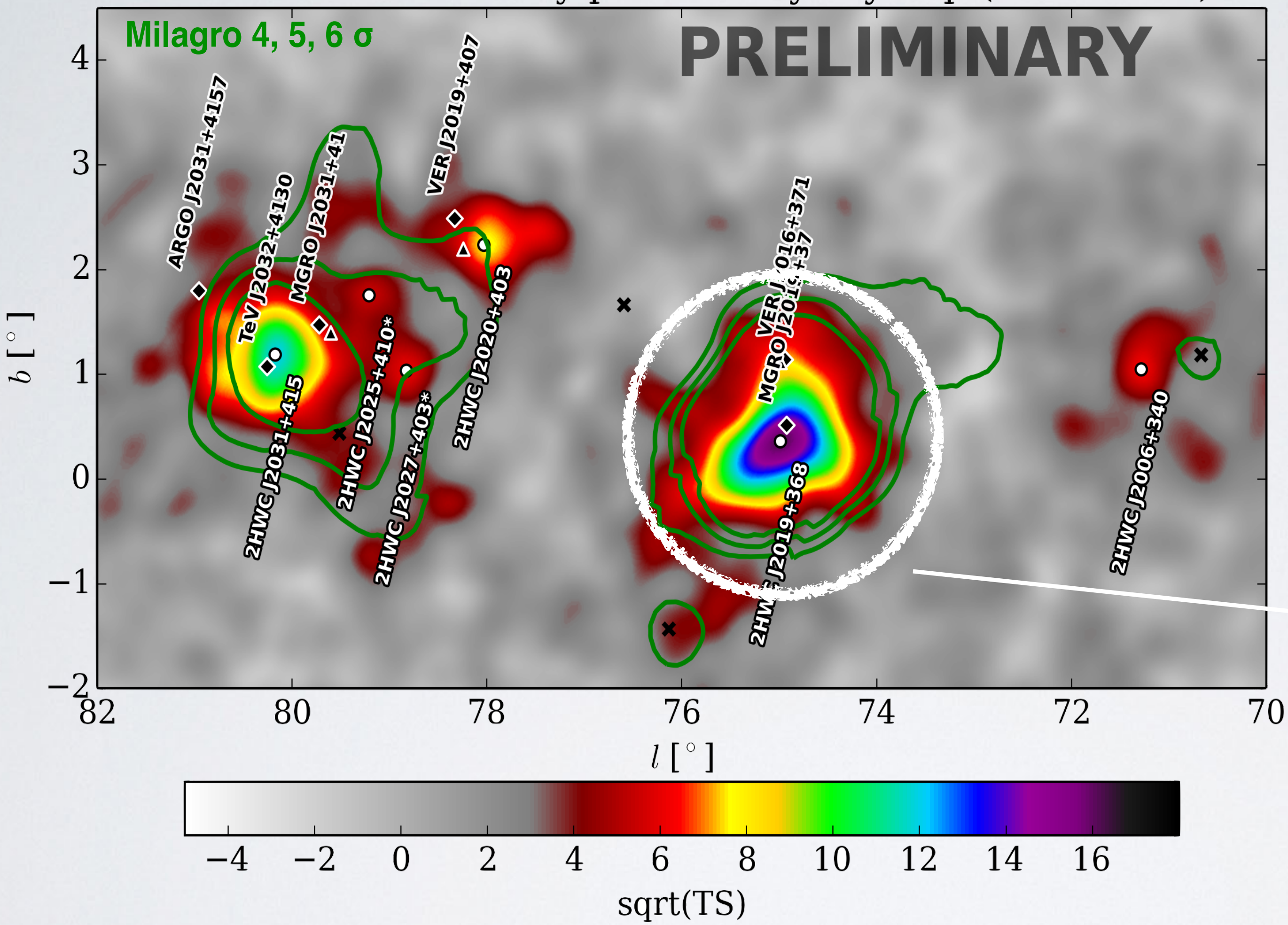


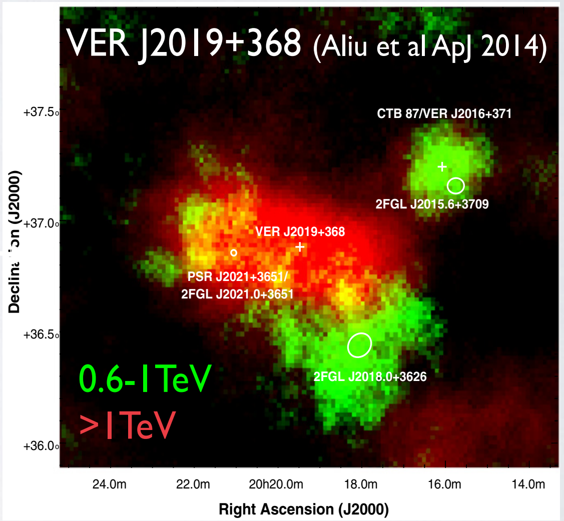
New TeV source
2HWC J1928+178
- ~8σ pre-trials
- coincident with PSR J1928+1746
- tail towards unidentified source 3FGL J1925.4+1727
- VERITAS point source upper limit ~1.4% of Crab

Cygnus Region

New TeV source 2HWCJ2006+340:
- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338

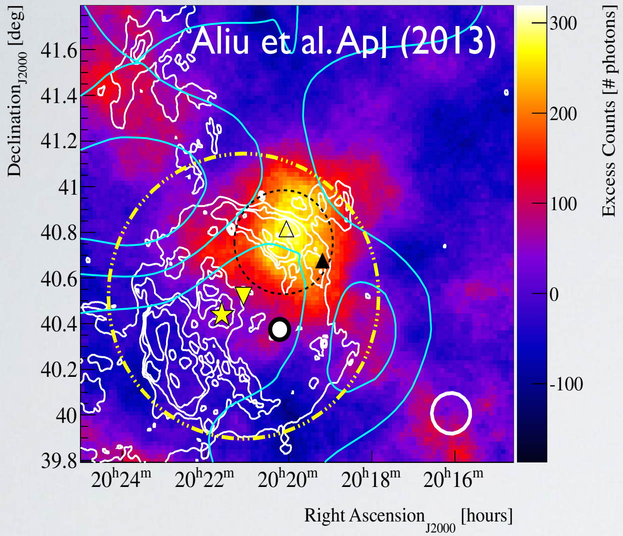
HAWC Pass 4 341-day preliminary skymap (2014-2015)

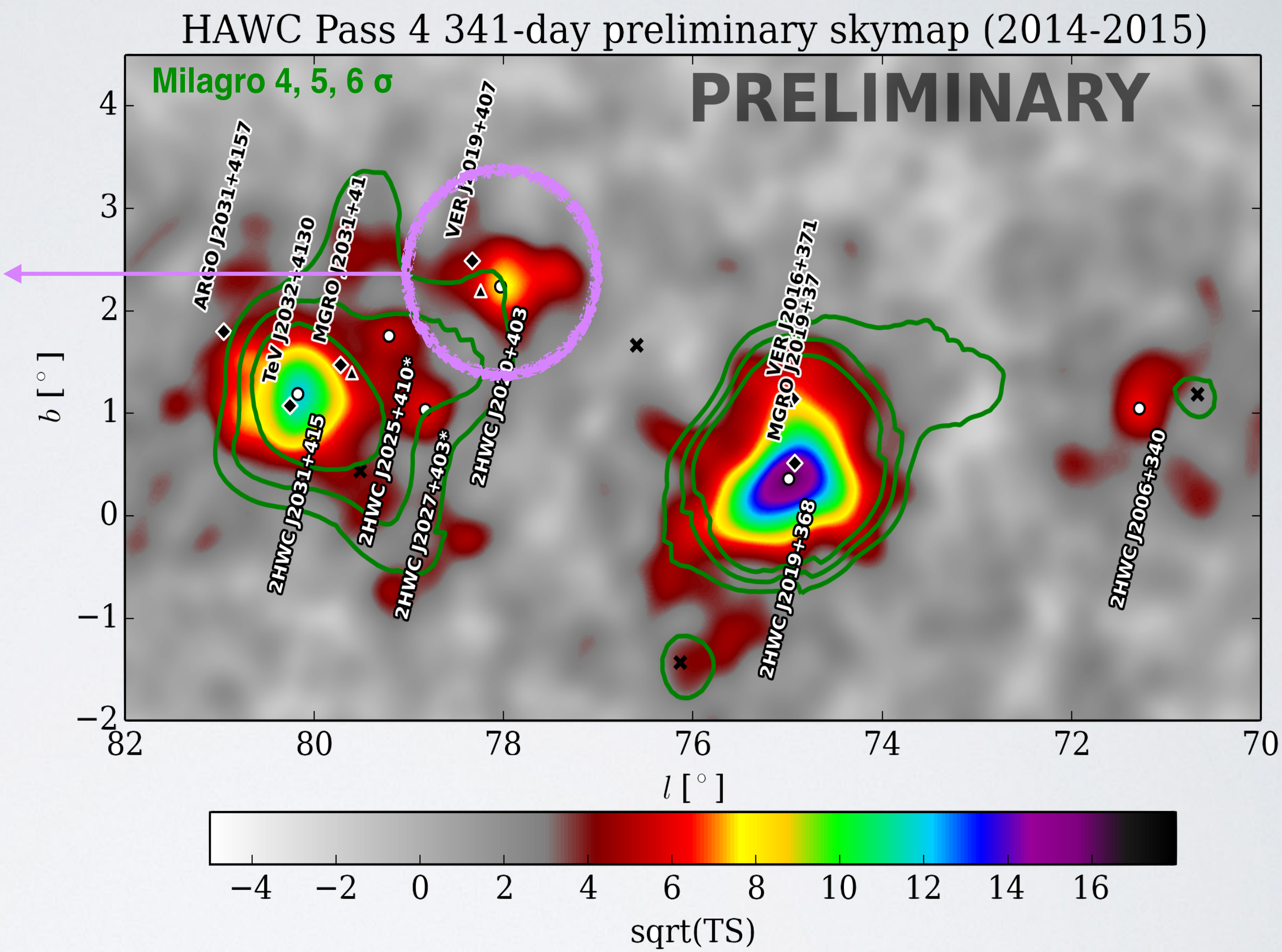




2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368
- extended emission including PSR J2021+3651 and HII region Sh 2-104

Cygnus Region

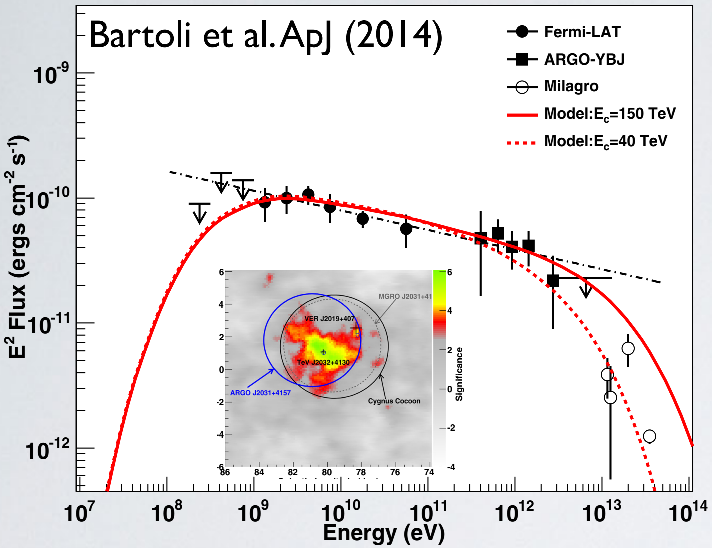


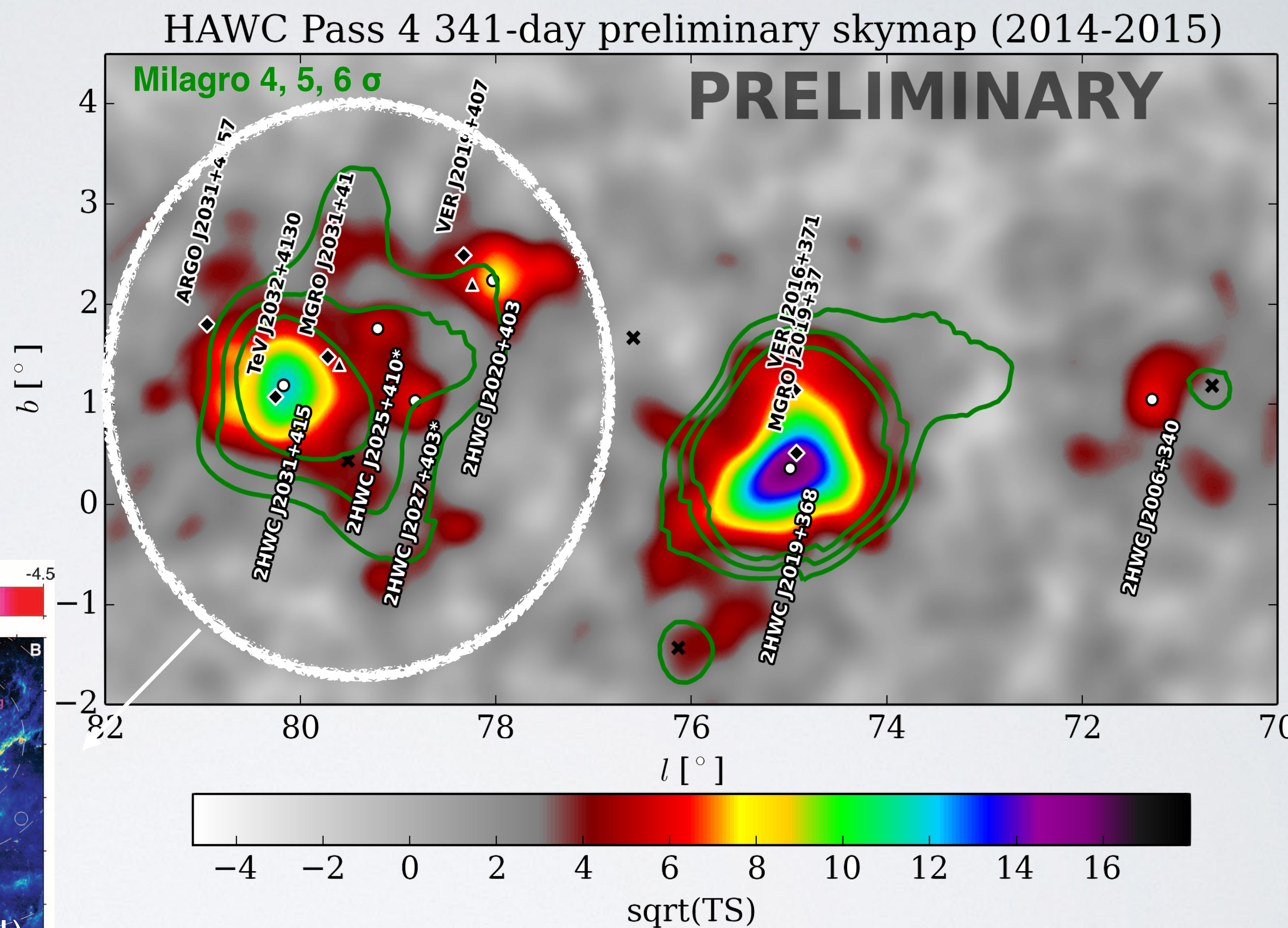


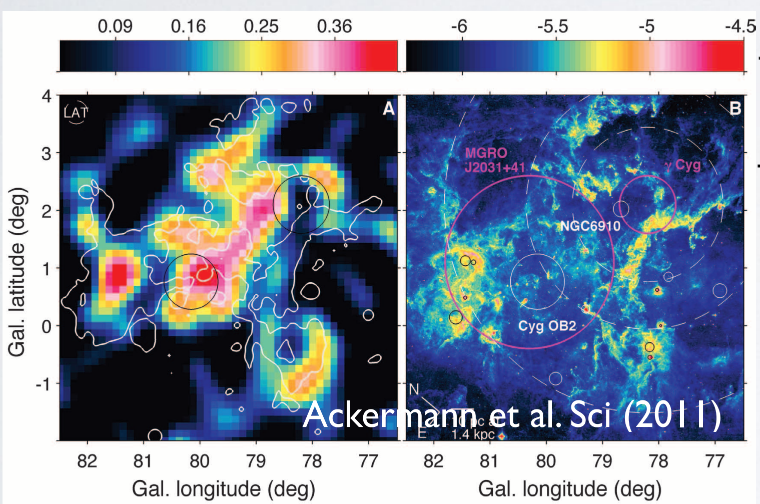
MGRO J2031+41 is resolved into two distinct TeV sources:

- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon / ARGO superbubble region

Cygnus Region



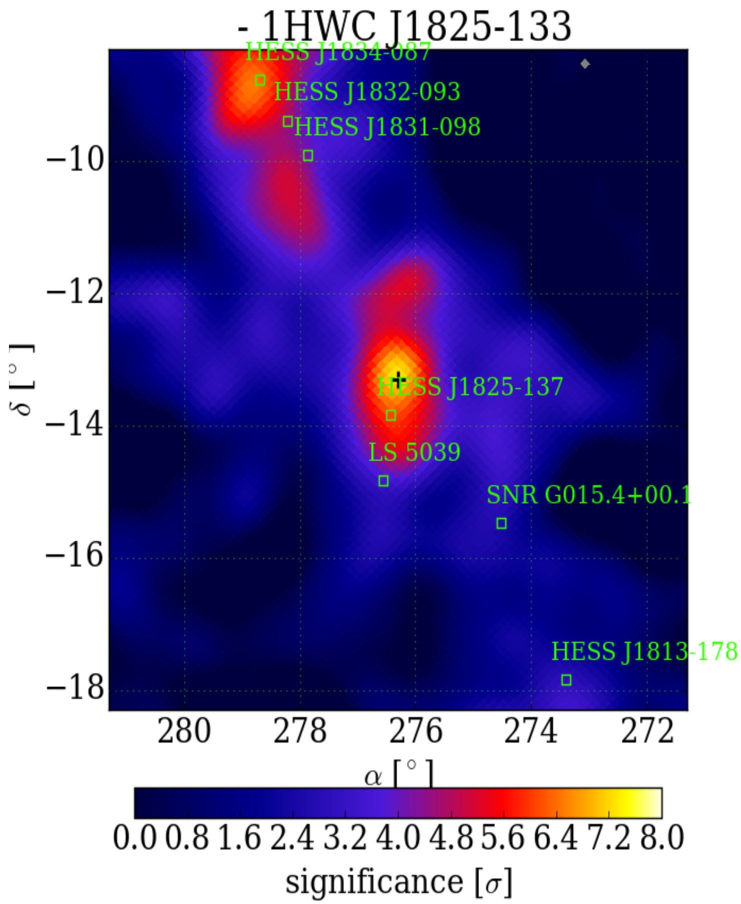




two distinct TeV sources:

- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon / ARGO superbubble region

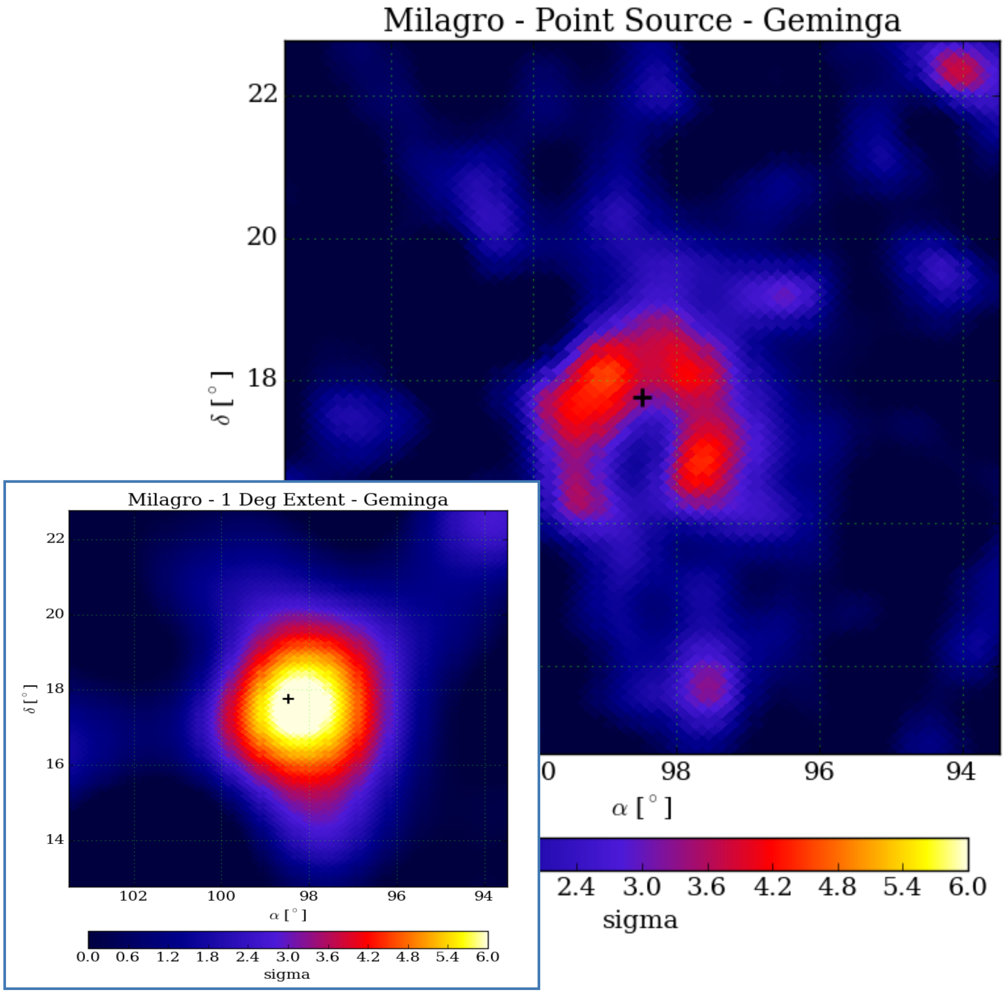
HAWC-111 Galactic Plane Analysis

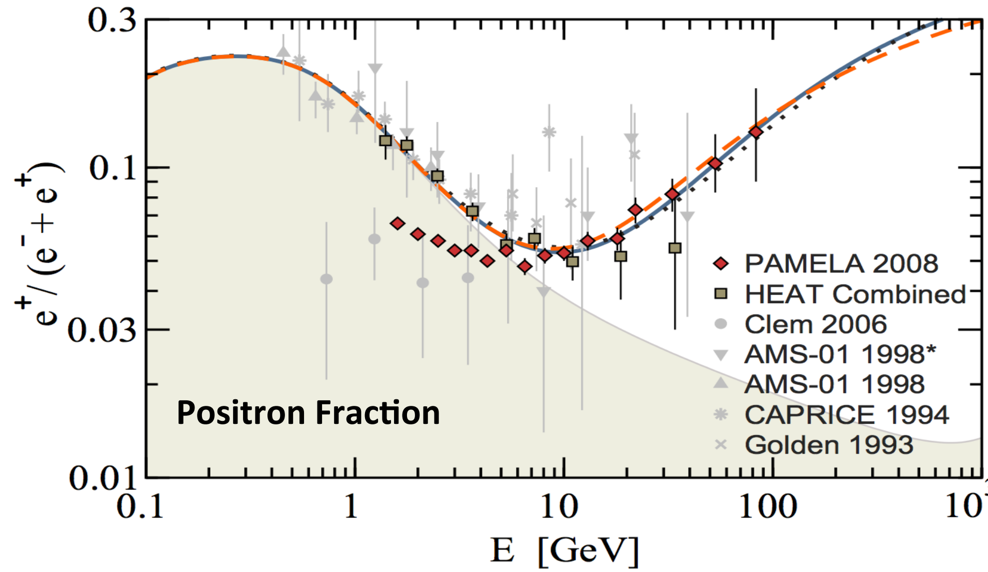


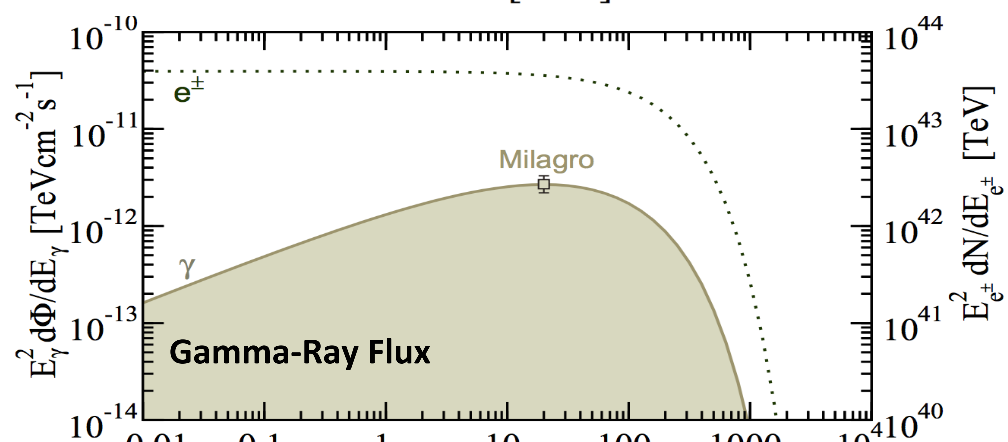
1HWC J1825-133

- Coincident with Pulsar Wind Nebula HESS J1825-137
- HESS Collaboration:
  - Claims spectrum hardens from $E^{-2.6}$ to E^{-2} from 1^{o} to the center of the pulsar.
  - Interprets as electrons cooling and streaming from the central pulsar.

Geminga



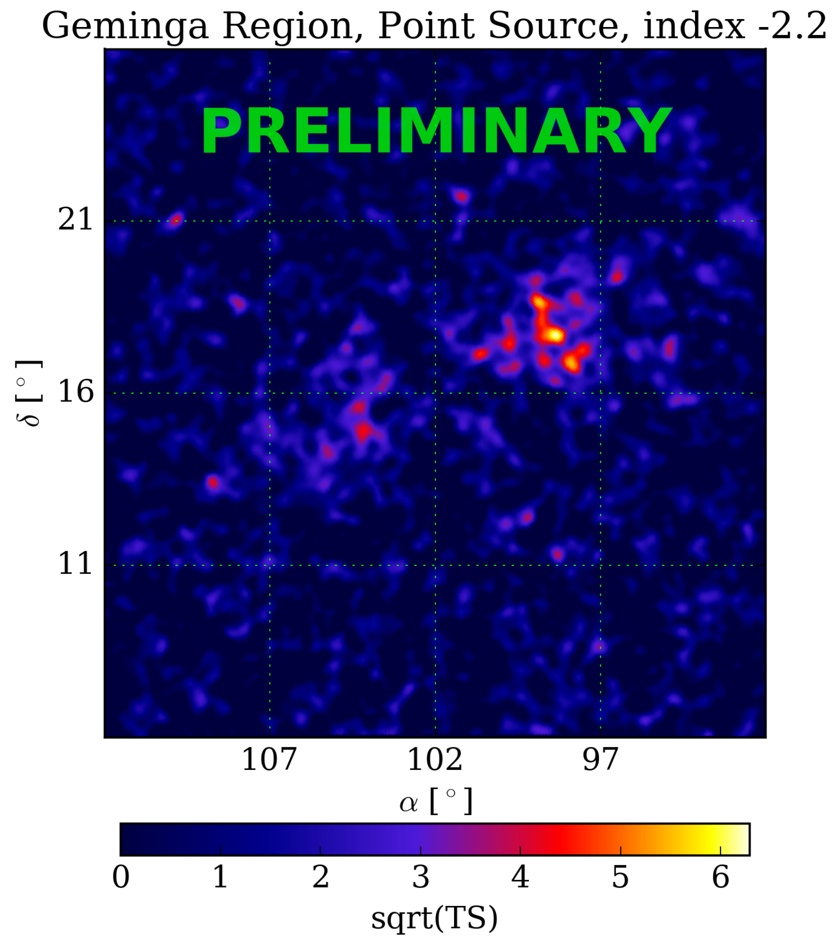


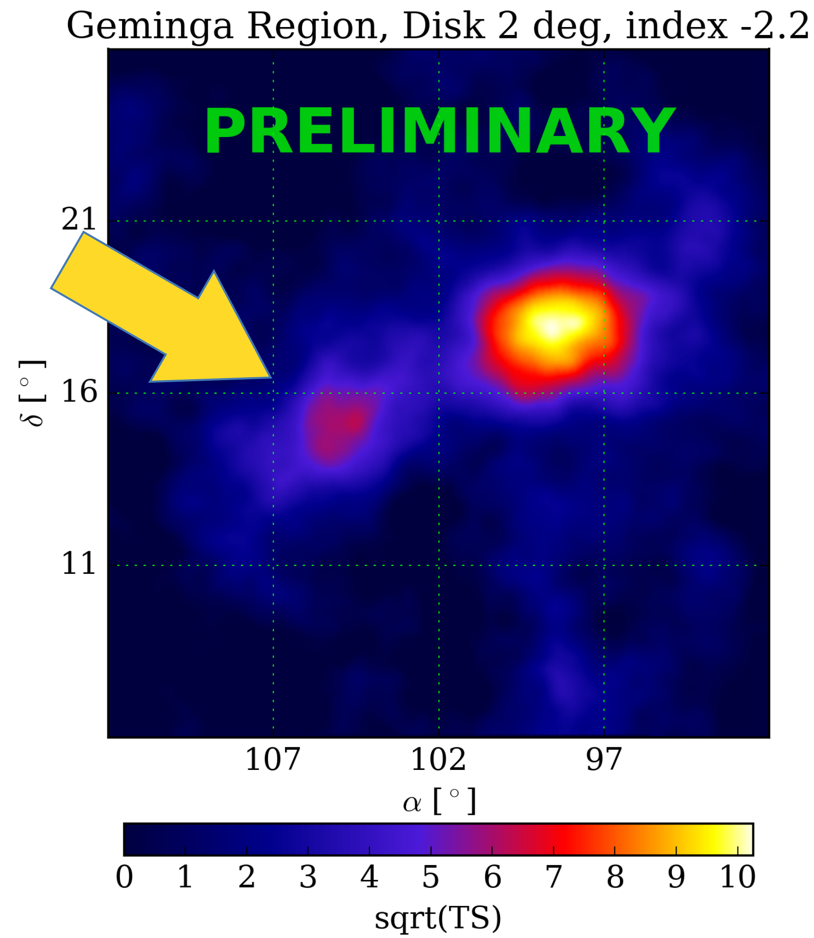


Yuksel, Kistler & Stanev. PRL. (2009)

- Extended TeV emission discovered by Milagro.
  - Contributor to positron excess?

Geminga Region





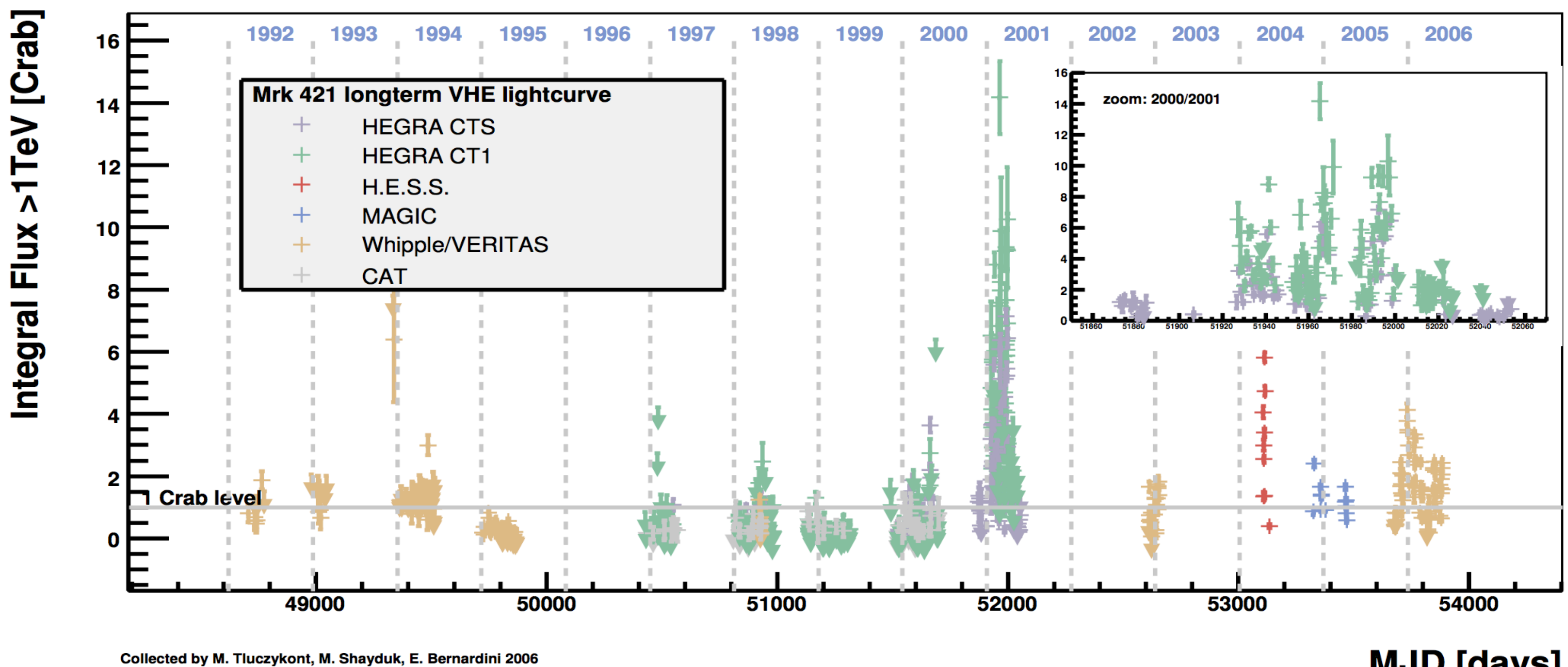
- Confirmation (~10σ pre-trial) of Geminga (PSR J0633+1746) by HAWC.
- Evidence (~6σ pre-trial) of a new extended source near PSR B0656+14.
- Both pulsars are similar in age and distance.

Paper in preparation!

Transients

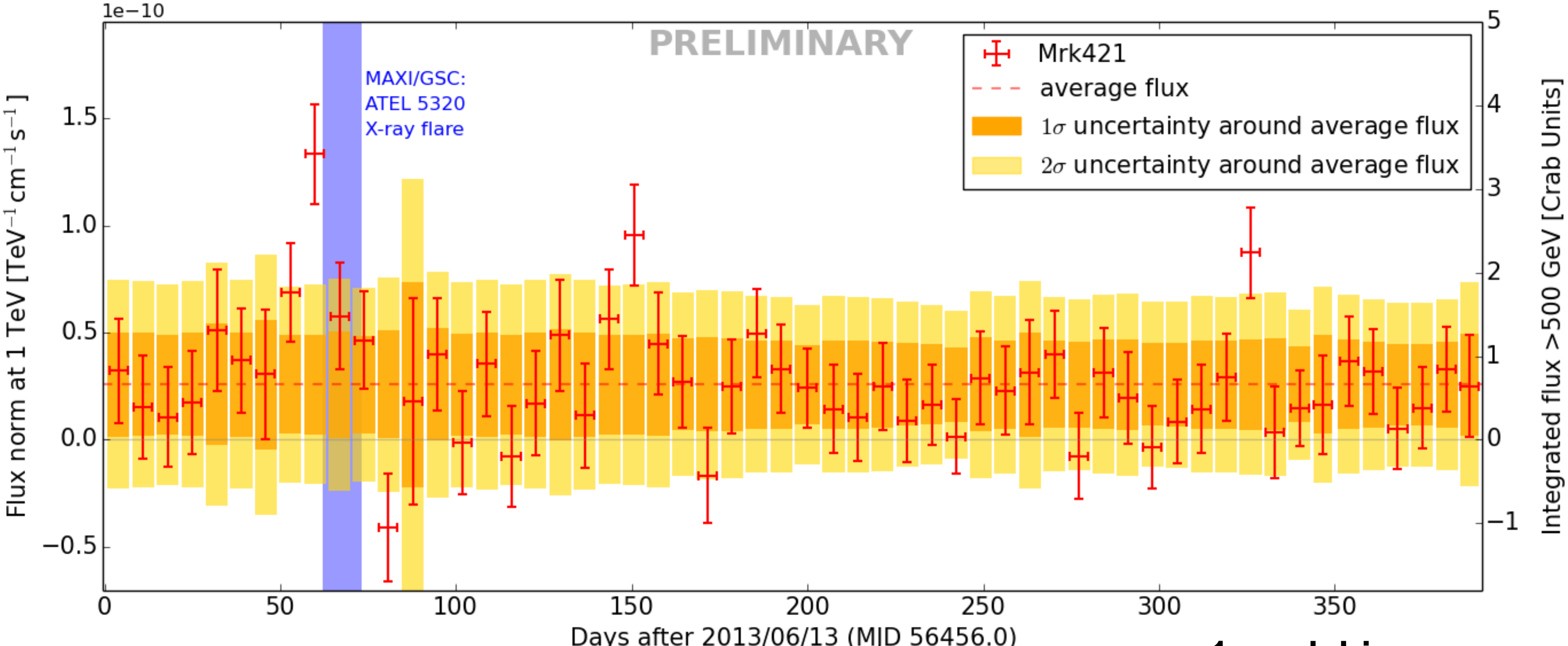
- Around 60 known TeV Active Galactic Nuclei (AGN), yet most of the extragalactic sky has not been surveyed.
- HAWC's 5σ sensitivity is (10, 1, 0.1) Crab in (3 min, 5 hrs, 1/3 yr).

A&A 524, A48 (2010)



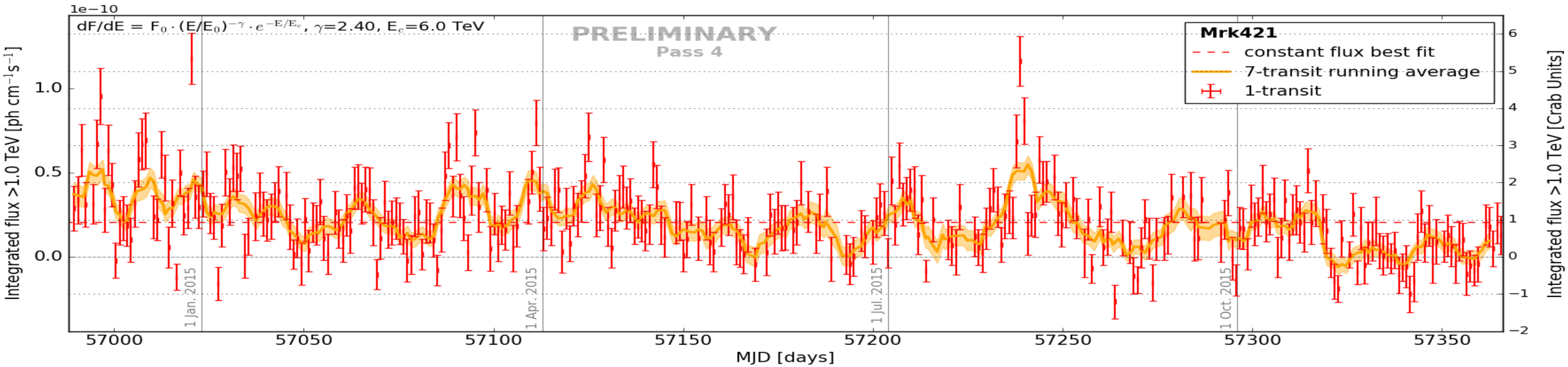
Mrk 421

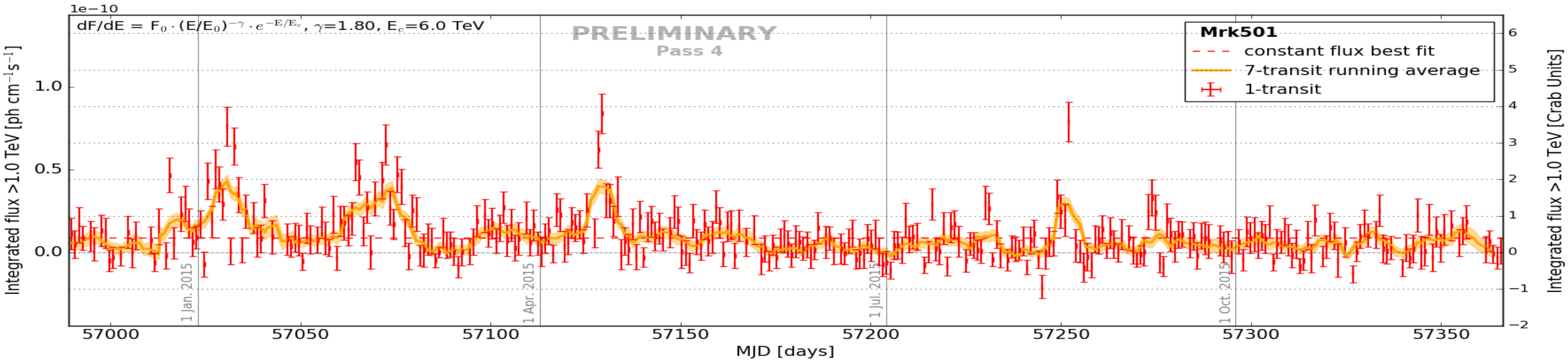
- Data from 2013/06/13 to 2014/07/09 in early HAWC data.
- HAWC coincident with the onset of a X-ray flare (ATEL 5320).



1 week bins

Mrk 412 & Mrk 501





First HAWC alert!

HAWC detection of increased TeV flux state for Markarian 501

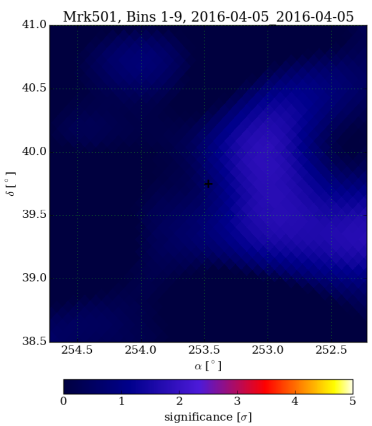
ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

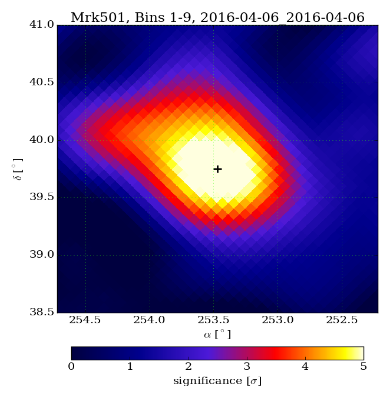
Tweet Recommend 15

The HAWC Observatory measured an increased gamma-ray flux from the direction of the BL Lac Markarian 501 (z=0.033) at the level of (4.88 +/- 1.05) x 10e-11 photons cm^-2 s^-1 above 1 TeV when averaged during the 6 hour transit over HAWC on April 6, 2016 (MJD 57484.31 - 57484.56) which is 2.2 times the average Crab flux observed by HAWC. For the following transit on April 7, 2016 (MJD 57485.30 - 57485.55), a decreased but still above-average flux of (2.78 +/- 0.09) x 10e-11 photons cm^-2 s^-1 was observed, 1.3 times the Crab flux seen by HAWC. The flux on April 6 lies 4 sigma above the average flux of 0.89 x 10e-11 photons cm^-2 s^-1 that was measured for this source by HAWC during the previous year. The flux level on April 7 is 2 sigma above this average and seems to indicate a declining but on-going high flux state. All flux values are obtained from a maximum likelihood fit under the assumption of a fixed spectral shape with power law index of 1.8 and exponential cut-off at 6 TeV. These spectral parameters are the best fit results for HAWC data from Markarian 501 collected between November 2014 and December 2015. HAWC is a TeV gamma ray water Cherenkov array located in the state of Puebla, Mexico that monitors 2/3 of the sky every day with an instantaneous field of view of ~2 sr. The HAWC contact people for this analysis are Robert Lauer (University of New Mexico, rjlauer@unm.edu) and Michelle Hui (Marshall Space Flight Center, c.m.hui@nasa.gov).

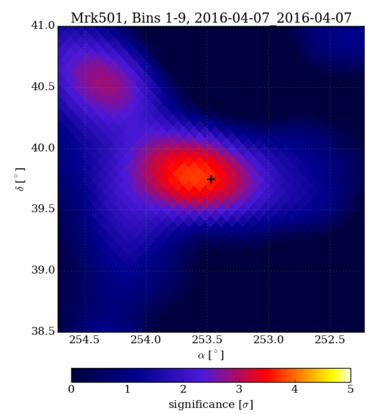
Astronomer's Telegram to alert community of activity.



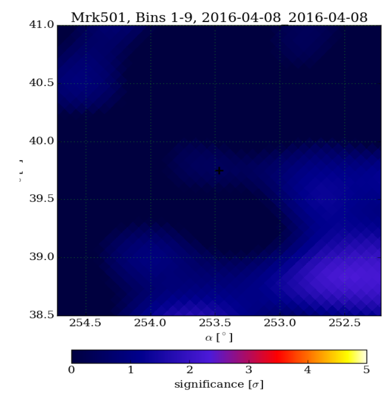
April 5, 2016



April 6, 2016



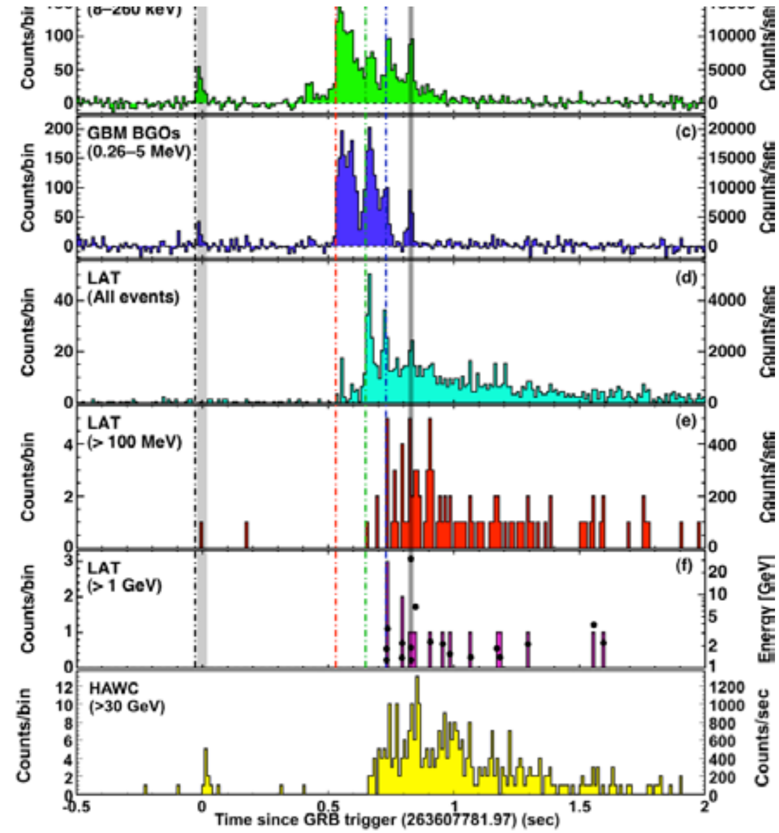
April 7, 2016



April 8, 2016

- HAWC has just started to provide prompt notification of flaring activity.
- Monitoring all gamma-ray sources visible to HAWC every day.

Perspectives for GRB detection



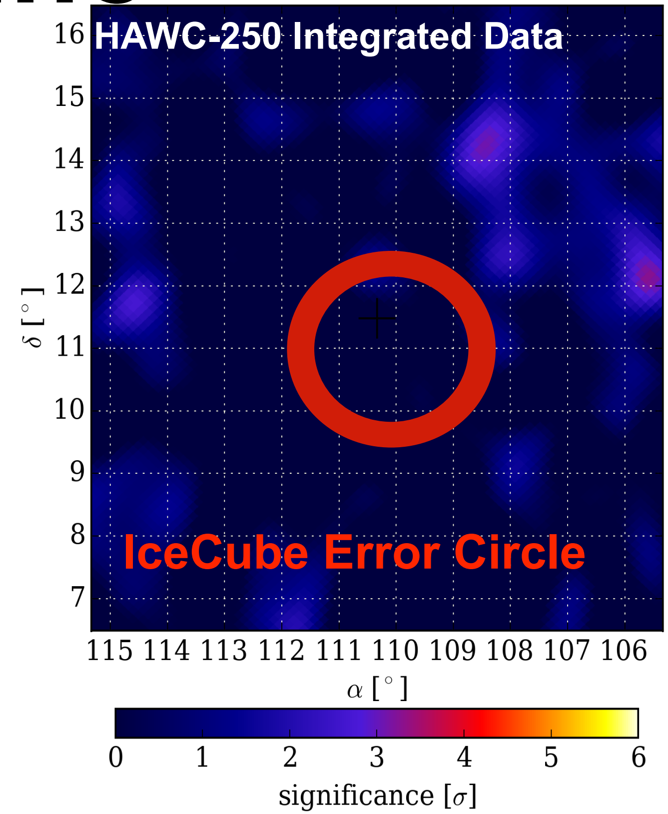
- Assume spectrum extends to 125 GeV and attenuation with EBL model of Gilmore
- HAWC: 200 events from GRB 090510 if near zenith
  ~few background events
- Major Improvements!
  – Low-threshold DAQ
  – 10-inch PMTs

→ HAWC would observe 100s of events for spectrum to only 31 GeV

HAWC Follow-up on 2.6 PeV IceCube Neutrino

IceCube Event

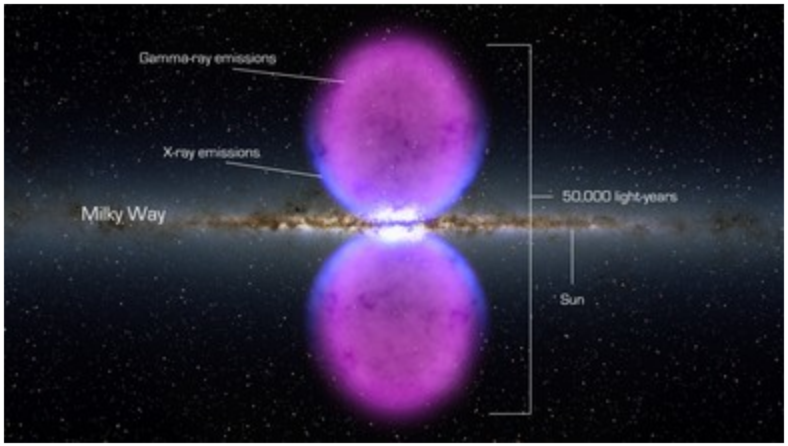
- Highest energy pointed astrophysical track-like event
- June 11, 2014, 4:54 UTC. (RA,Dec) = (110.3, 11.5)
- HAWC-111 live (pass1). Several hours out of HAWC's FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
  - All searches consistent with cosmic-ray background.

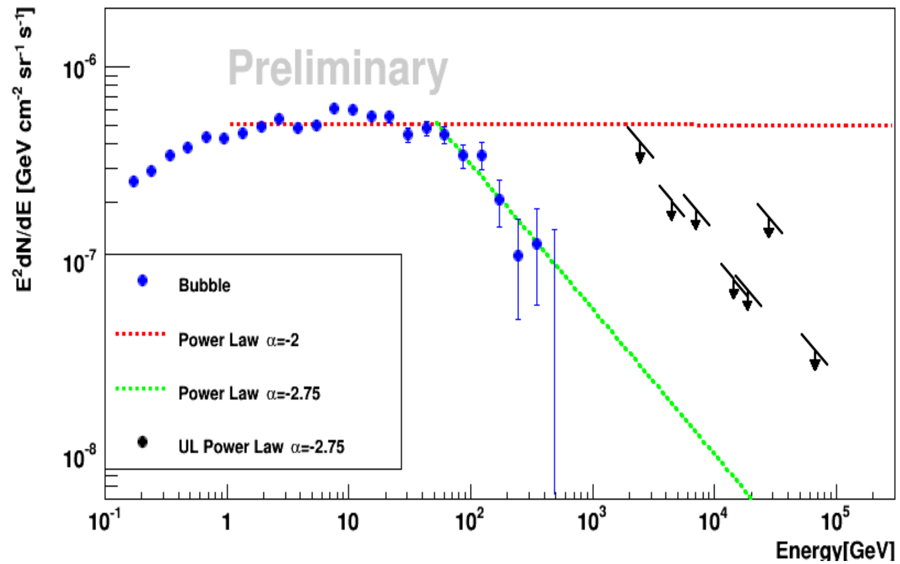


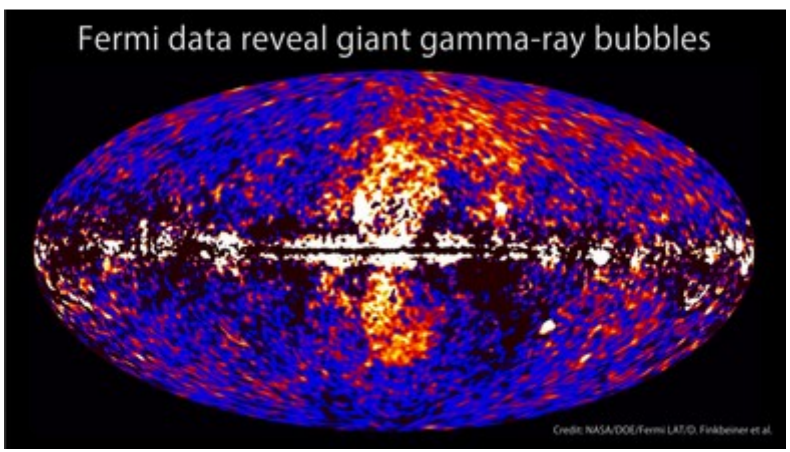
The steady neutrino flux, assuming it is evenly divided among N_s sources (IceCube, PRL 2014), should be detectable in HAWC in a year if photons are not attenuated.
We can set constraining limits on every IceCube event in the HAWC FOV.

IceCube ATel: #7856
HAWC Follow-up ATel: #7868

Fermi Bubbles







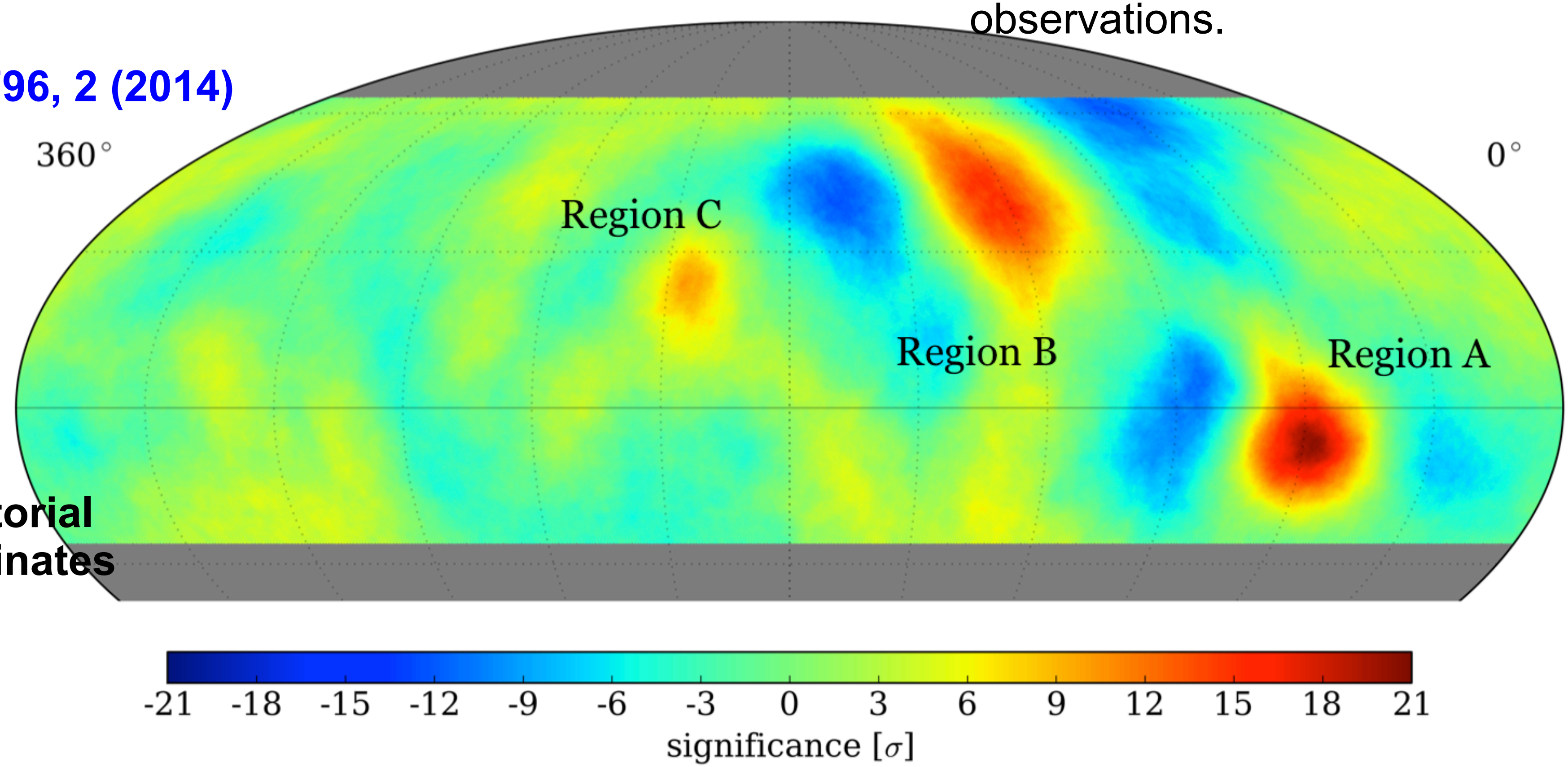
- Large-scale, non-uniform structures extending above and below the Galactic center.
- Both leptonic and hadronic model fit Fermi data.
- HAWC provides the firsts limits at TeV energies.
- Hard spectrum is unlikely (analysis in progress).

Cosmic Ray Anisotropy

- Small-scale (<60º). Large scale removed.
- 10º smoothing applied.
- 8.6 x 10^{10} events over 181 days.

- Three significant excess:
  - Region A: strongest. Harder spectrum than the background at 10TeV, consistent with Milagro.
  - Region B most extended.
  - Region C,confirms ARGO-YBJ observations.

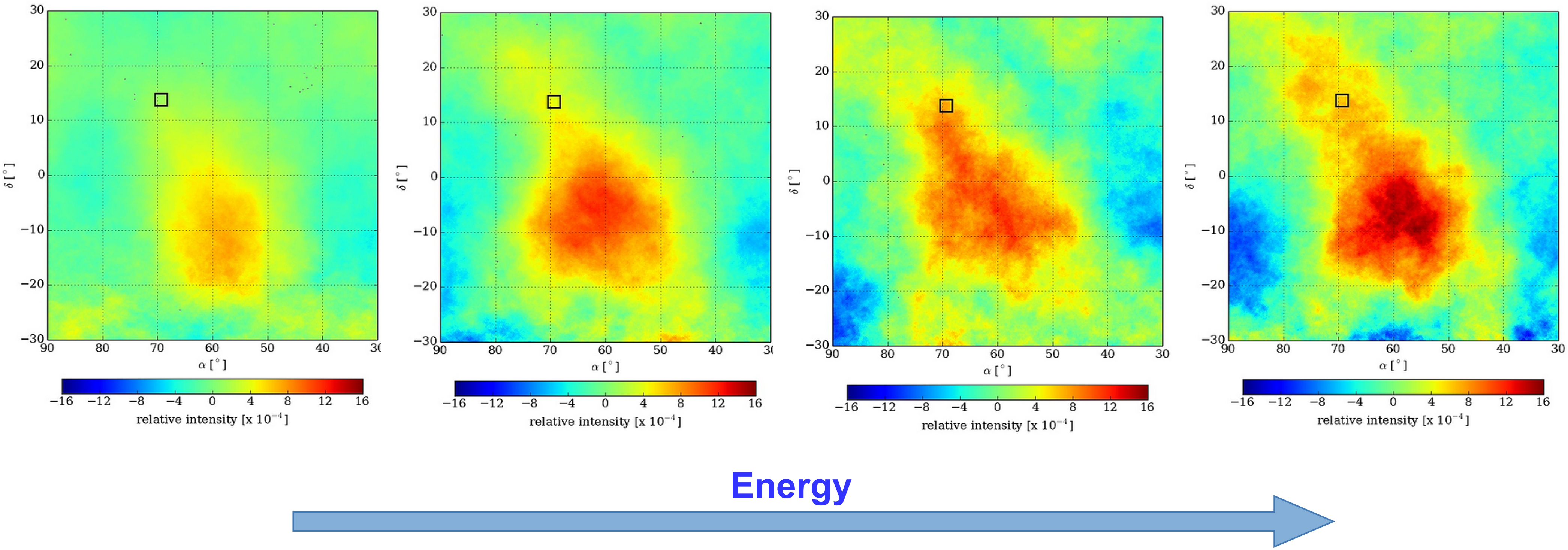
ApJ 796, 2 (2014)



Equatorial coordinates

Cosmic Ray Anisotropy

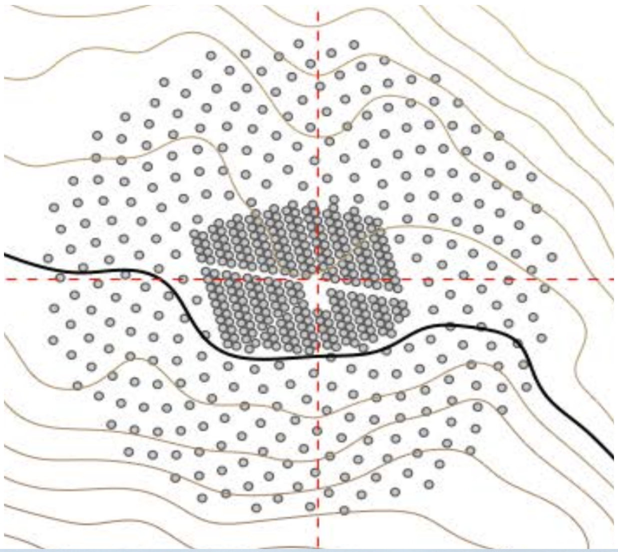
- Region A has a spectrum harder than the cosmic-ray background.



Other topics

- Diffuse emission.
- Dark matter searches.
- Extragalactic background light.
- Solar physics.
- Horizontal muons studies.
- Etc…

The Future of HAWC



Near future:

- HAWC will add more detectors to enhance the sensitivity above 10 TeV.
- Outriggers will help to accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Plans for ~300 tanks of 2500 liter tanks (1/80 HAWC tank).
- Funded by LANL, Mexico, MPIK. Firsts tests ongoing.

Future:

- HAWC South: Southern complement for CTA.
- Needs to be better: higher altitude, larger area, improved hadronic rejection, improved shower sensitivity.

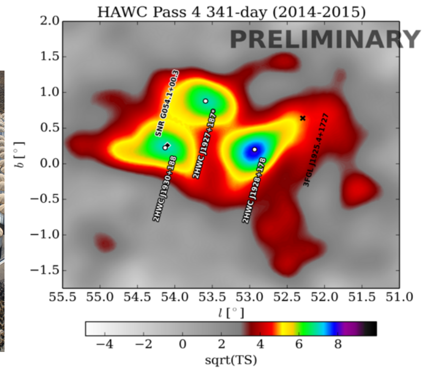
Summary

Detector:

- HAWC is a second generation of EAS which started full operations in March 2015.
- HAWC is about 1 order of magnitude more sensitive than the predecessors EAS . It surveys more than half of the sky every day.
- Expected to run at least for 5yr, reaching 20mCrab sensitivity.

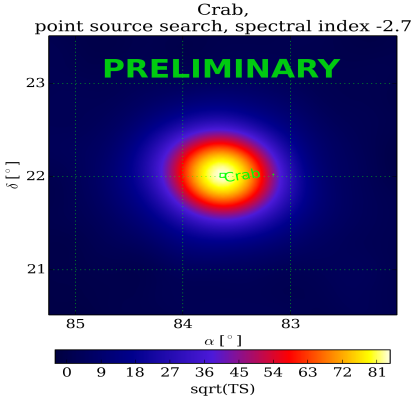
First Results:

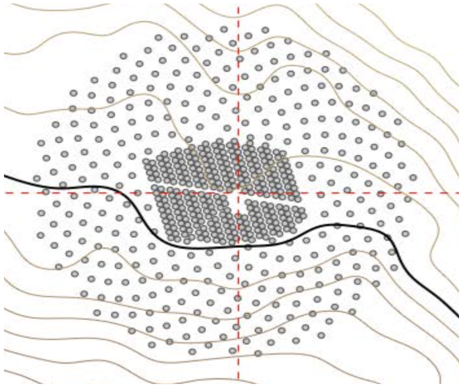
- Galactic Plane survey (new sources).
- Flaring blazars observations.
- Geminga detection, etc.



Status:

- More than one year of data.
- First catalog, papers on the pipeline.
- First public transient alert.

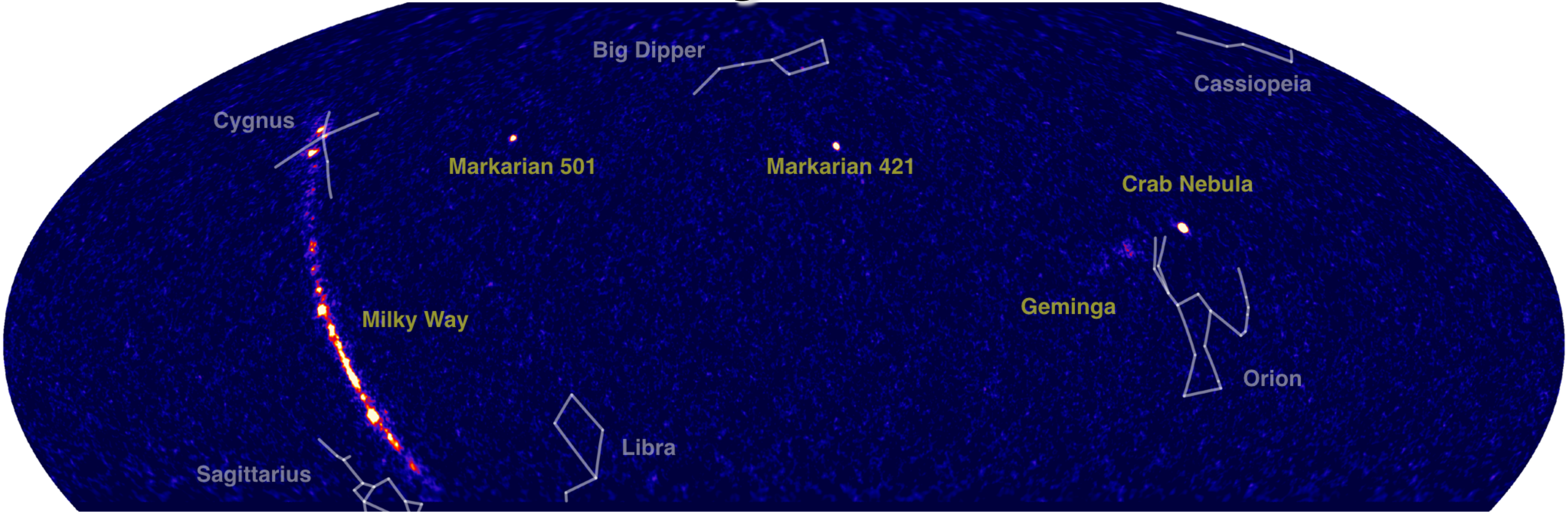




Future:

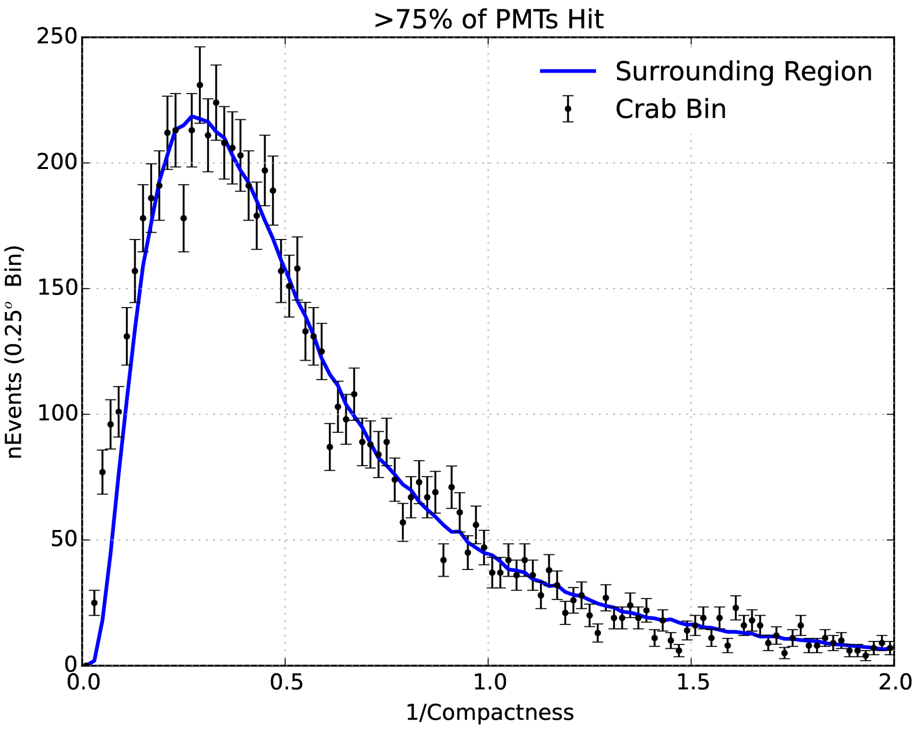
- Outriggers, HAWC South.

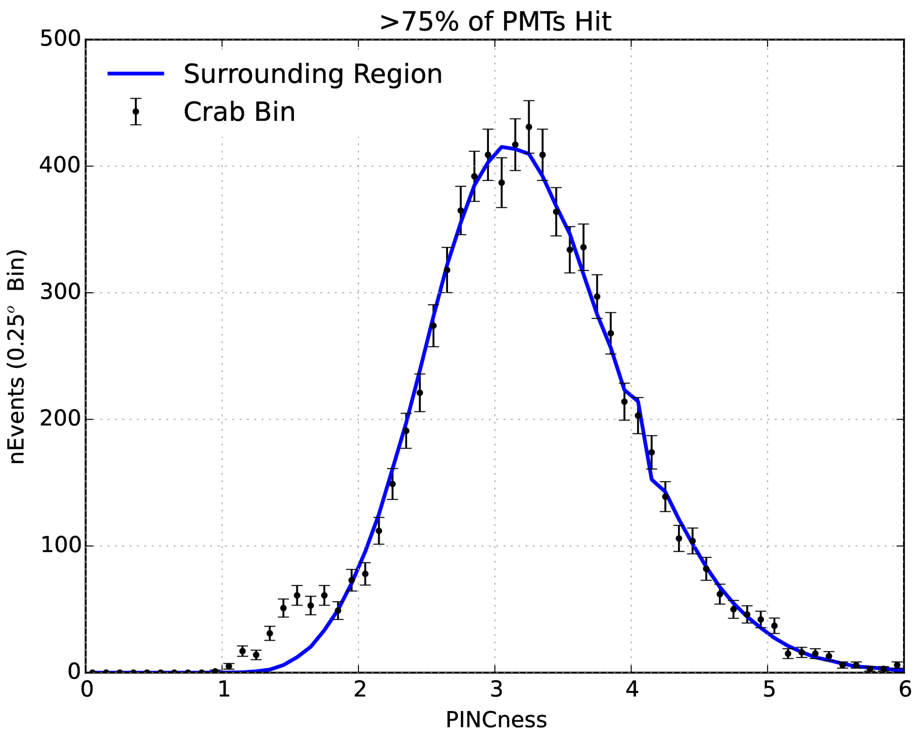
Thanks for your attention!



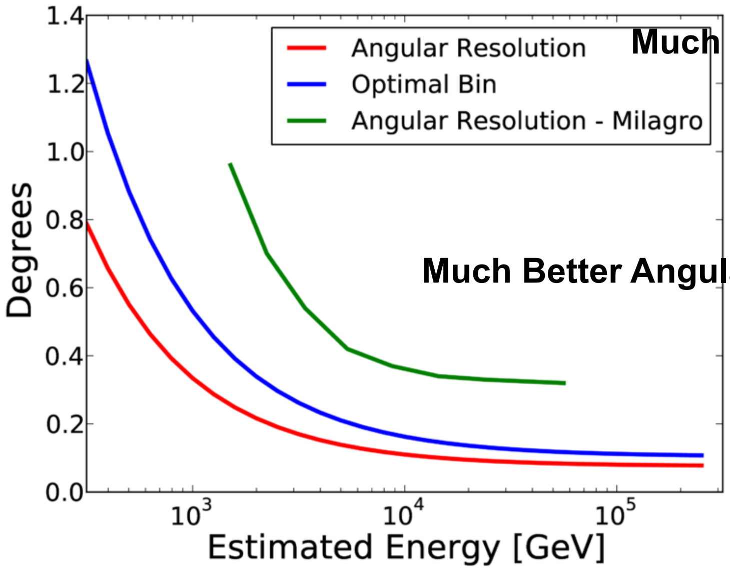
Back-up slides

γ/h separation



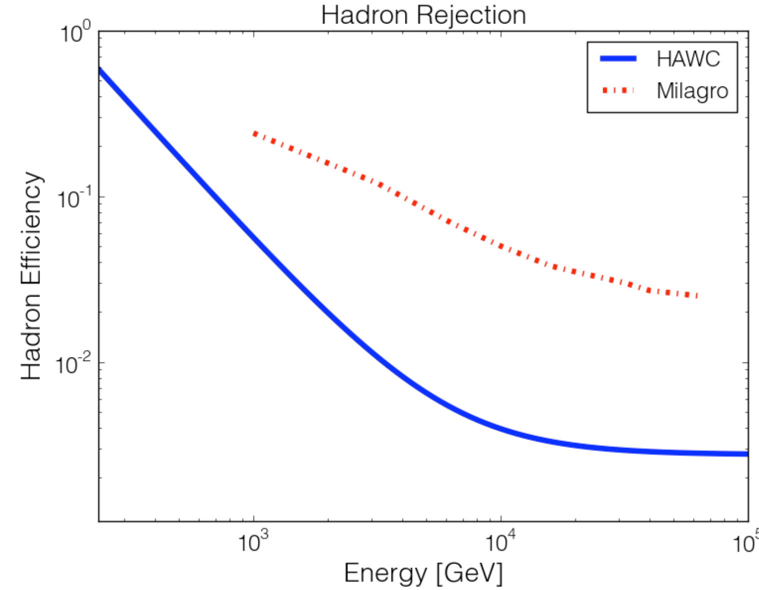


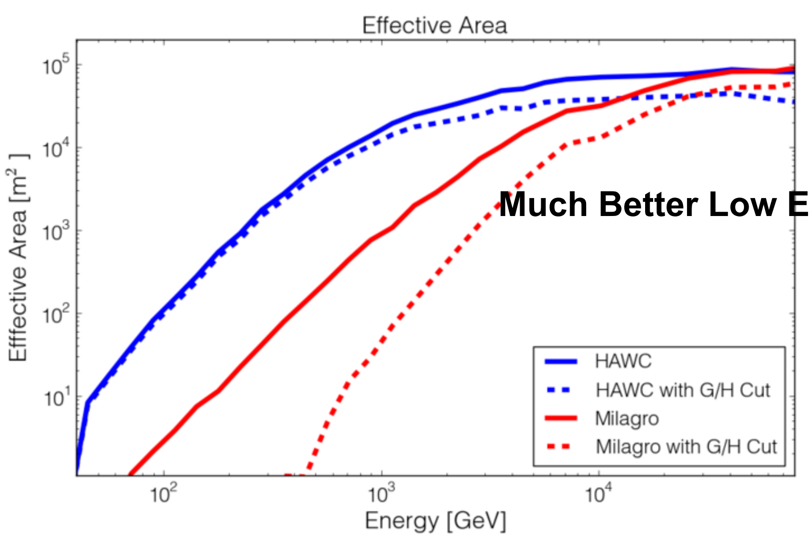
HAWC Performance



Much Better Background Rejectio

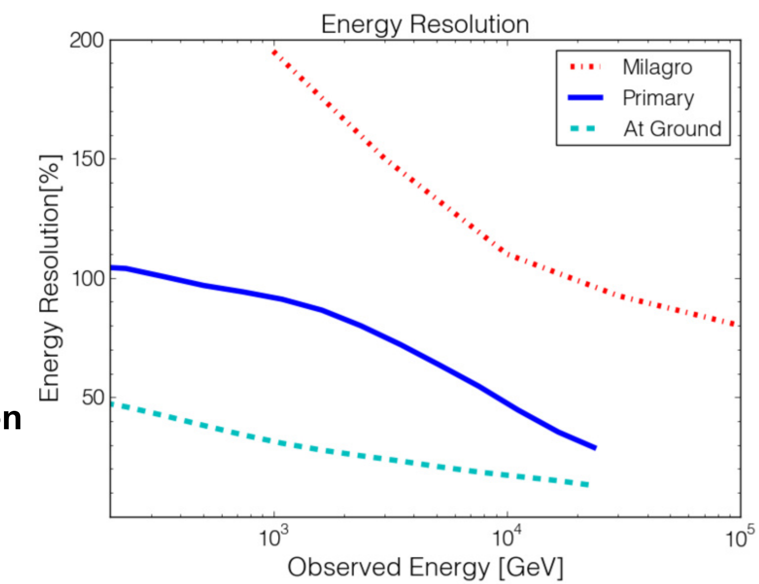
Much Better Angular Resolution





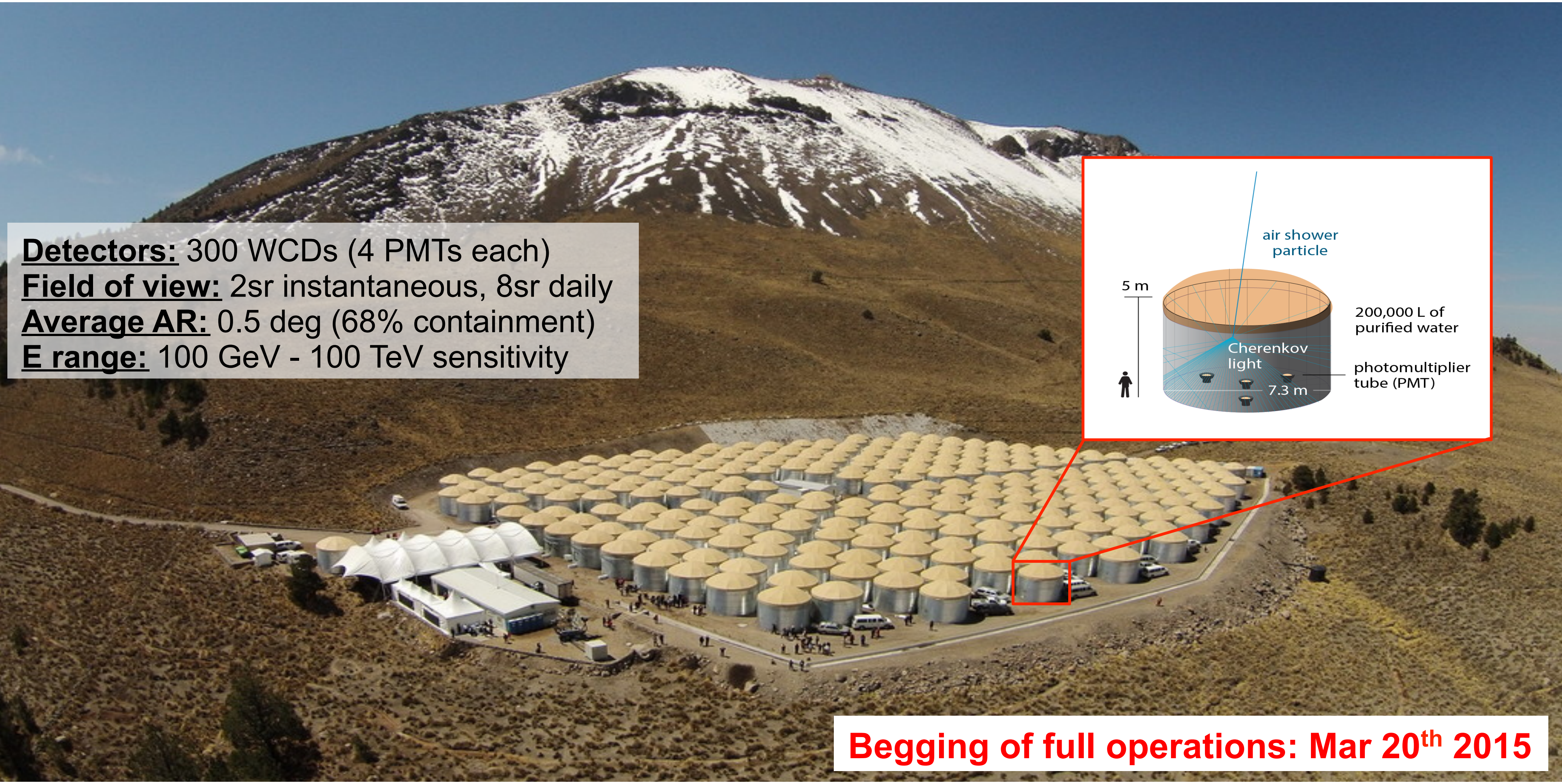
Much Better Low Energy Response

Better Energy Resolution



Overall x15 Milagro sensitivity

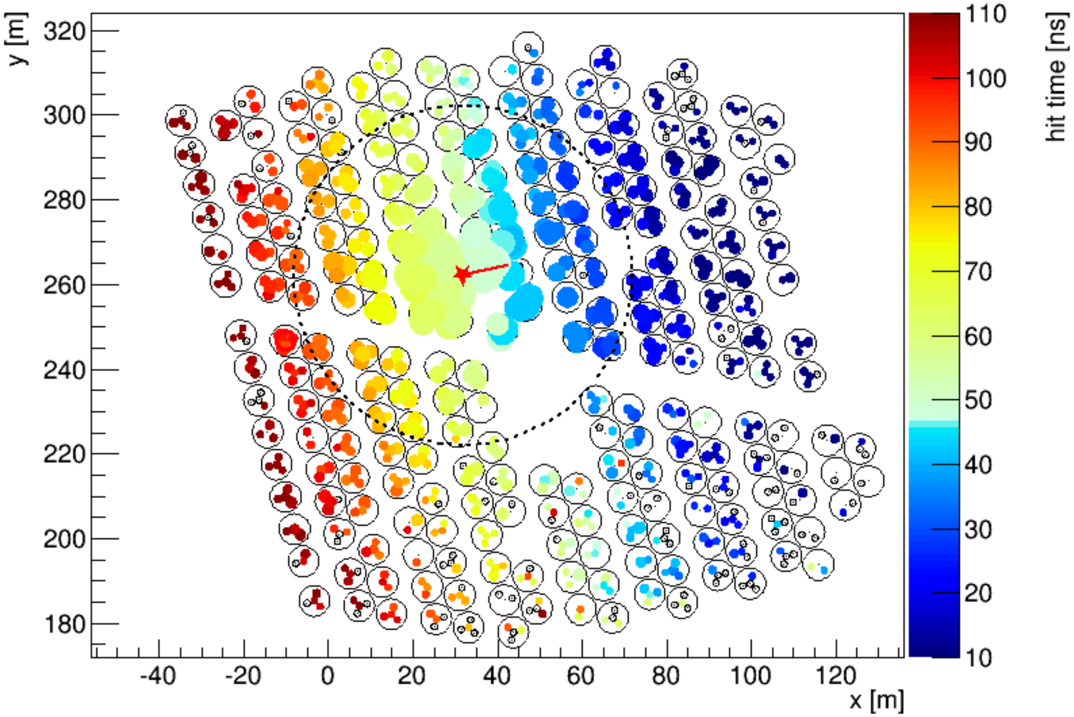
HAWC Inauguration

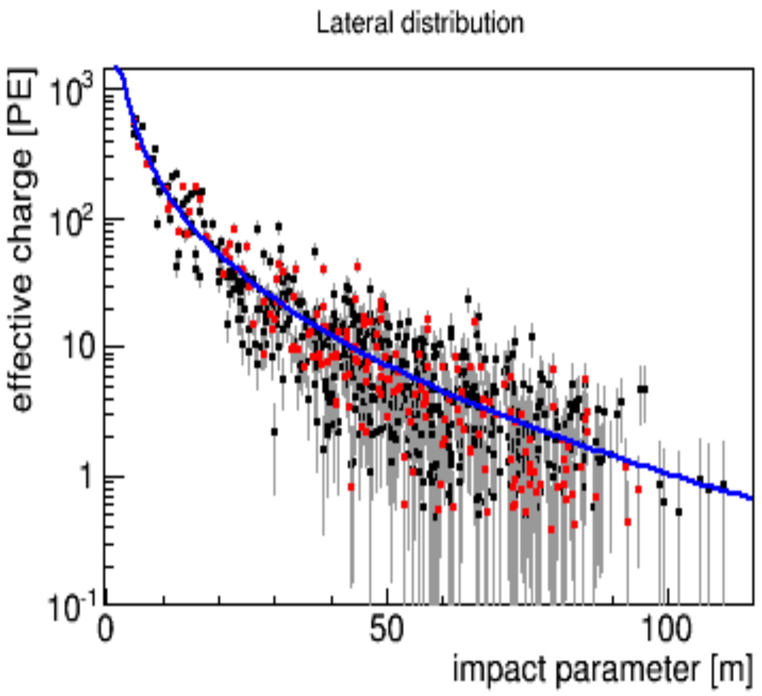


Detectors: 300 WCDs (4 PMTs each)
Field of view: 2sr instantaneous, 8sr daily
Average AR: 0.5 deg (68% containment)
E range: 100 GeV - 100 TeV sensitivity

Begging of full operations: Mar 20th 2015

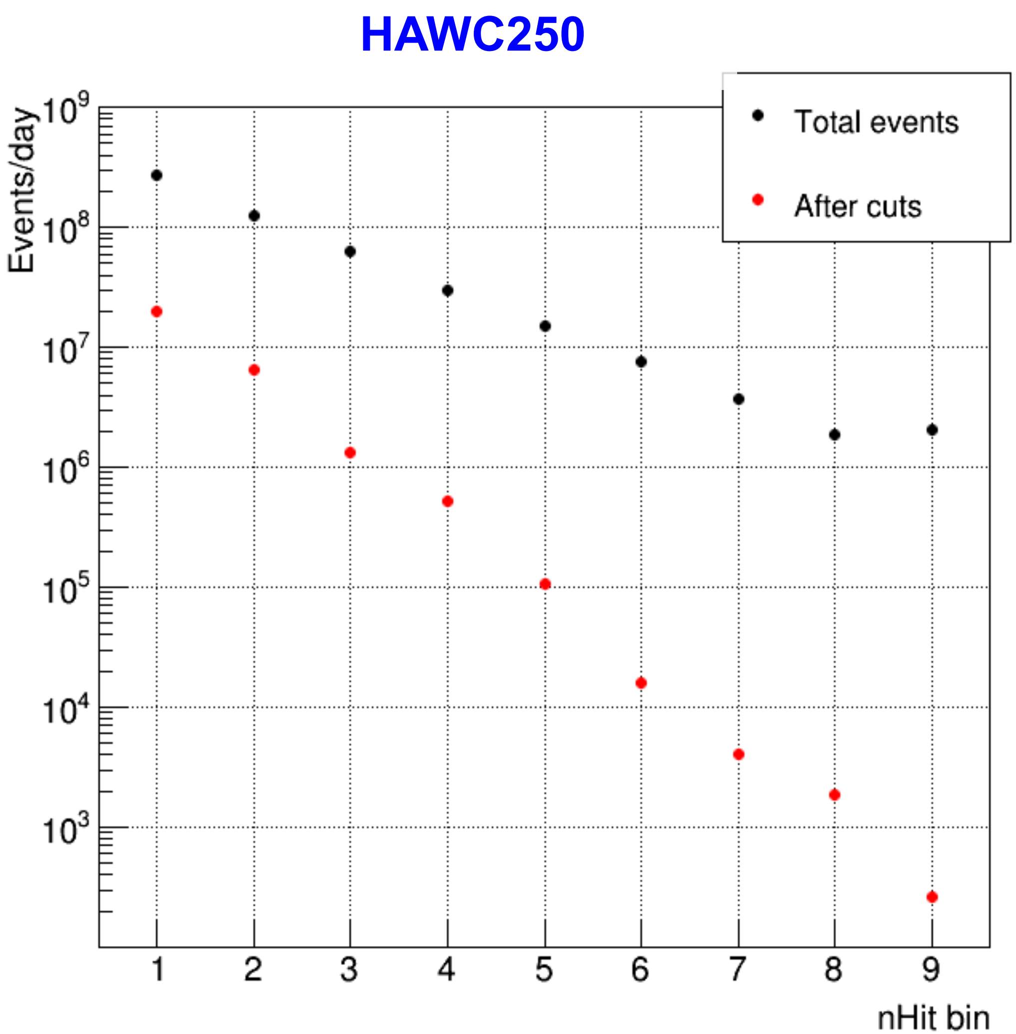
Crab gamma-ray candidate





- Event reconstructed within 0.4° of the Crab Nebula.

Data Selection



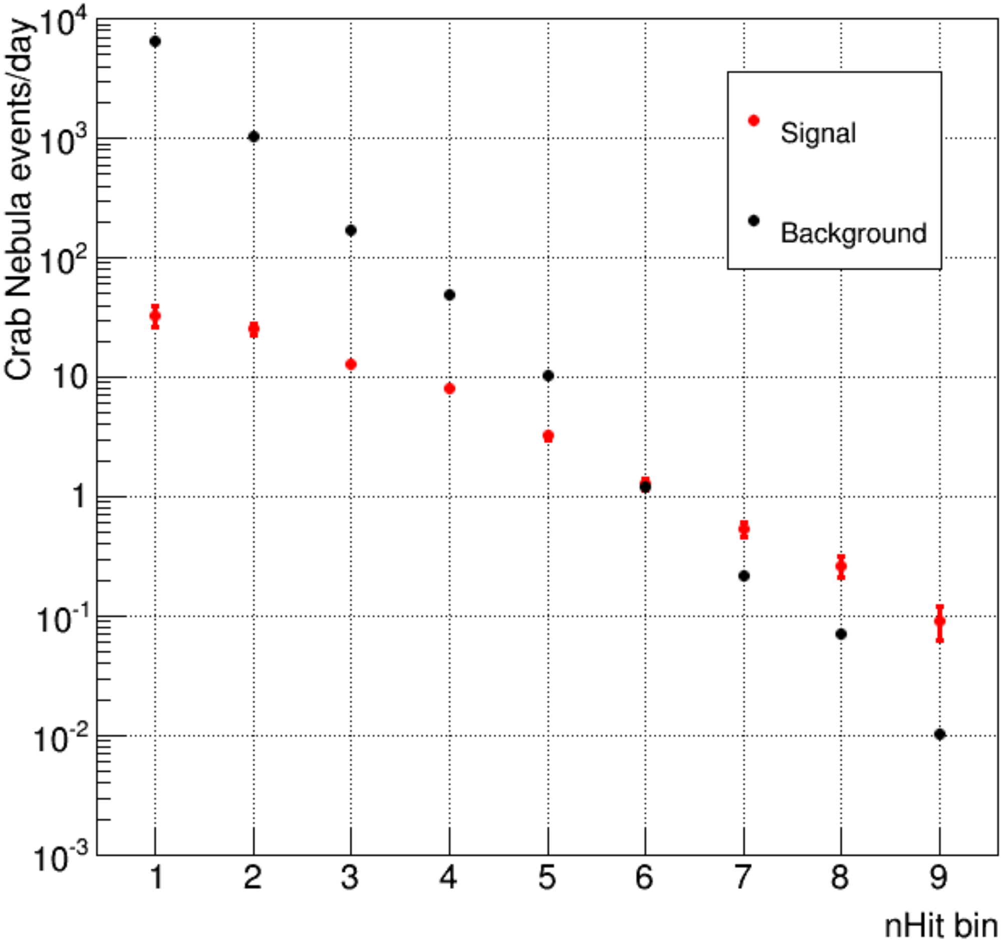
BIN 1: 7-10%, ~0.6 TeV **BIN 9: 84-100%, ~25 TeV**

- Divide the data in 9 analysis bins (nHit bins) based on the % of PMTs triggered in an event.
- First bin is defined for a given passing rate (5 kHz for HAWC250).
- The following bins are defined to decrease the rate by a factor 2.
- Apply G/H cuts, optimized on data to maximize the Crab significance:

Current HAWC G/H separation:
A. Smith (#397) poster 1 GA, July 30th 3.30pm

Data Selection

HAWC250

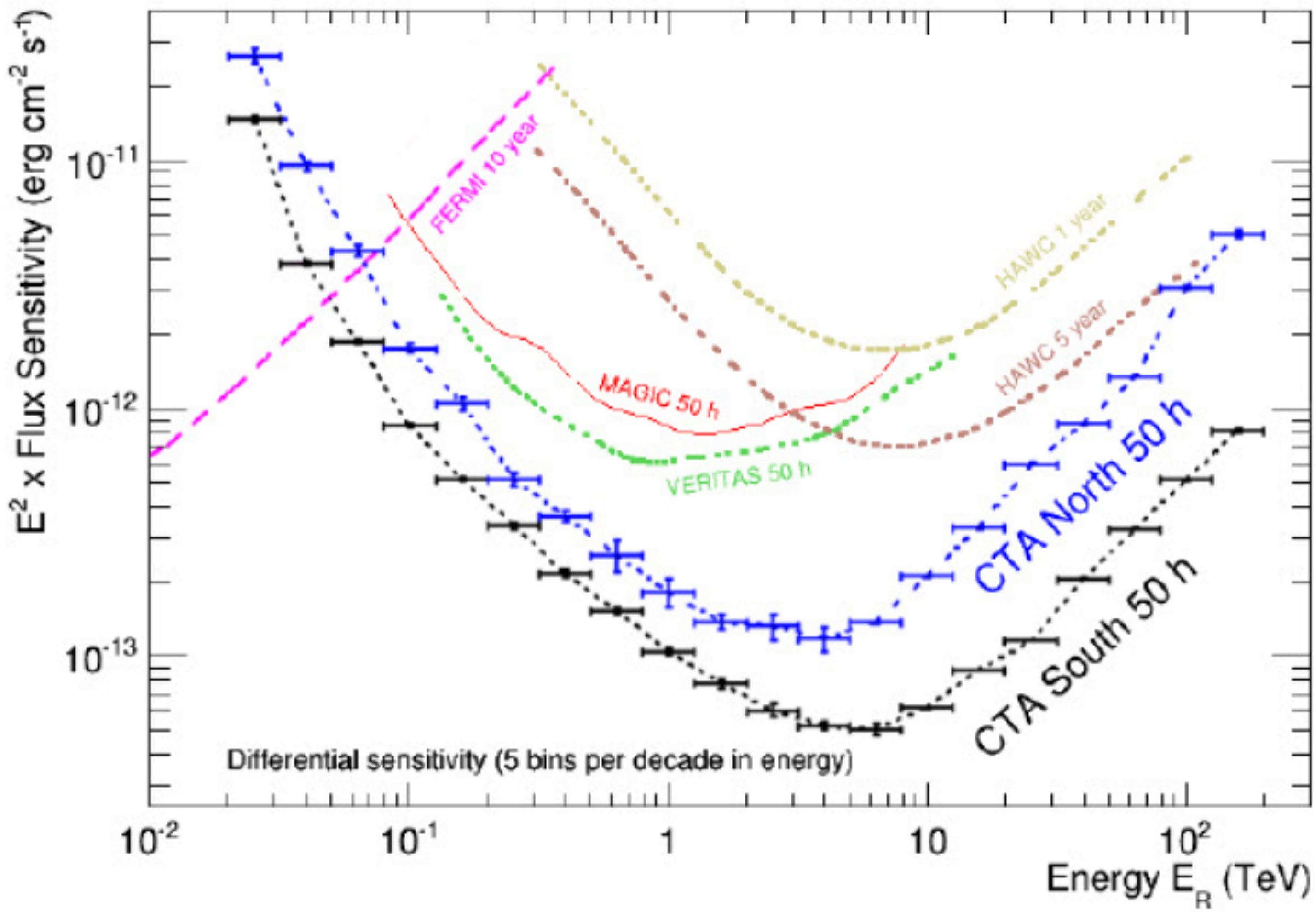


- For the **Crab Nebula** analysis we use circular angular bins (a.k.a. top-hat).
- We estimate the background using the direct integration technique:

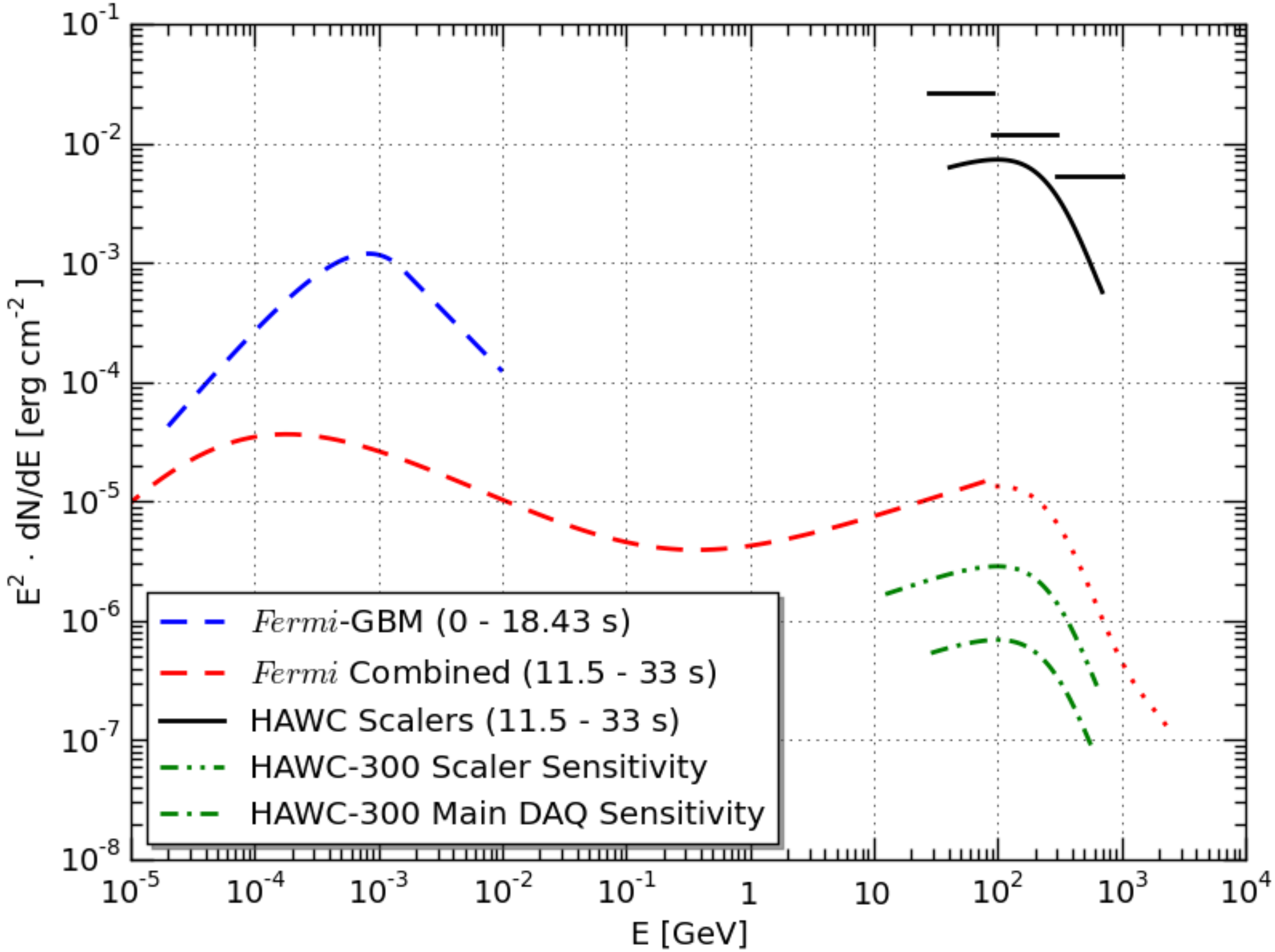
  Astrophys. J. **595** (2003) 803-811

- The signal is defined as the excess over the background.
- Almost 10:1 (signal:back) in bin 9.

CTA-HAWC sensitivity

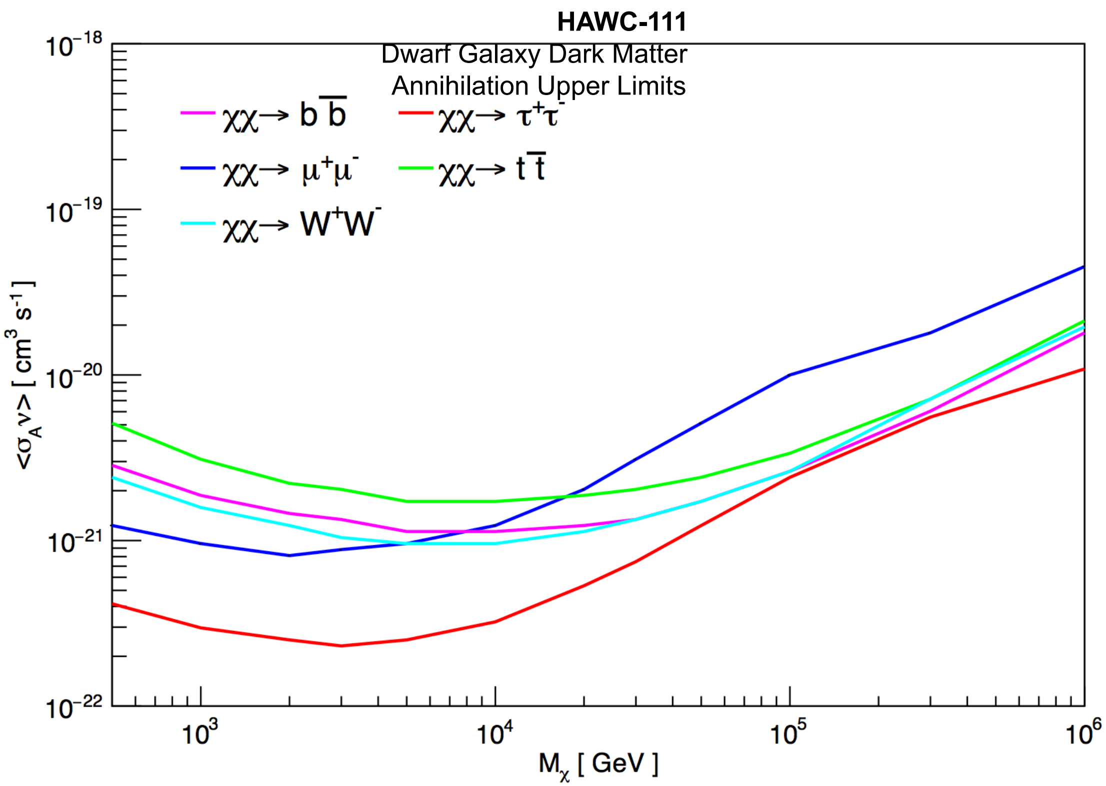


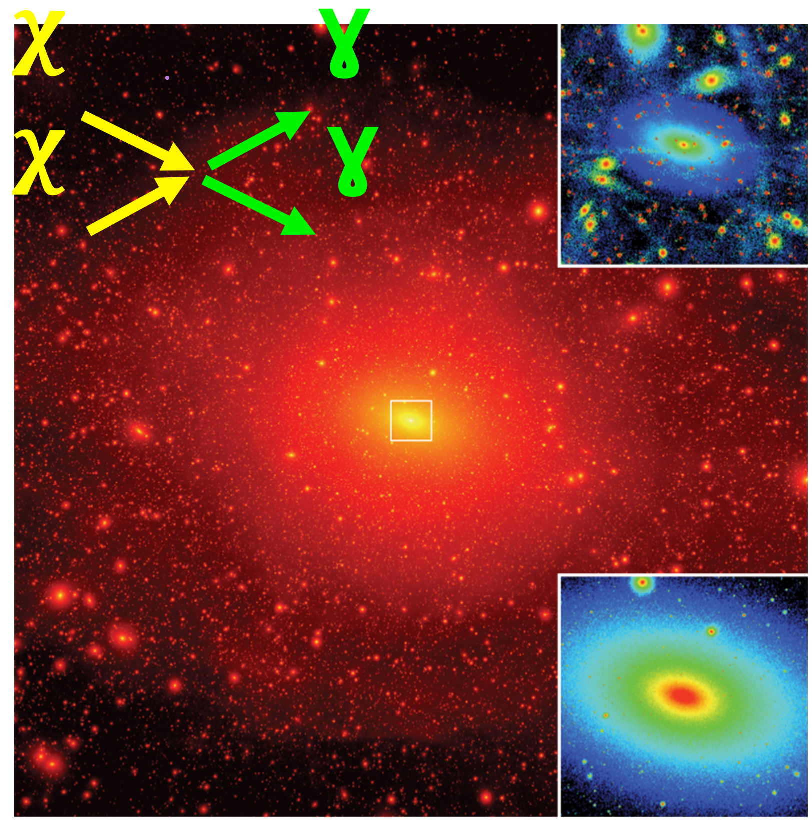
GRB 130427A limits



HAWC DM limits

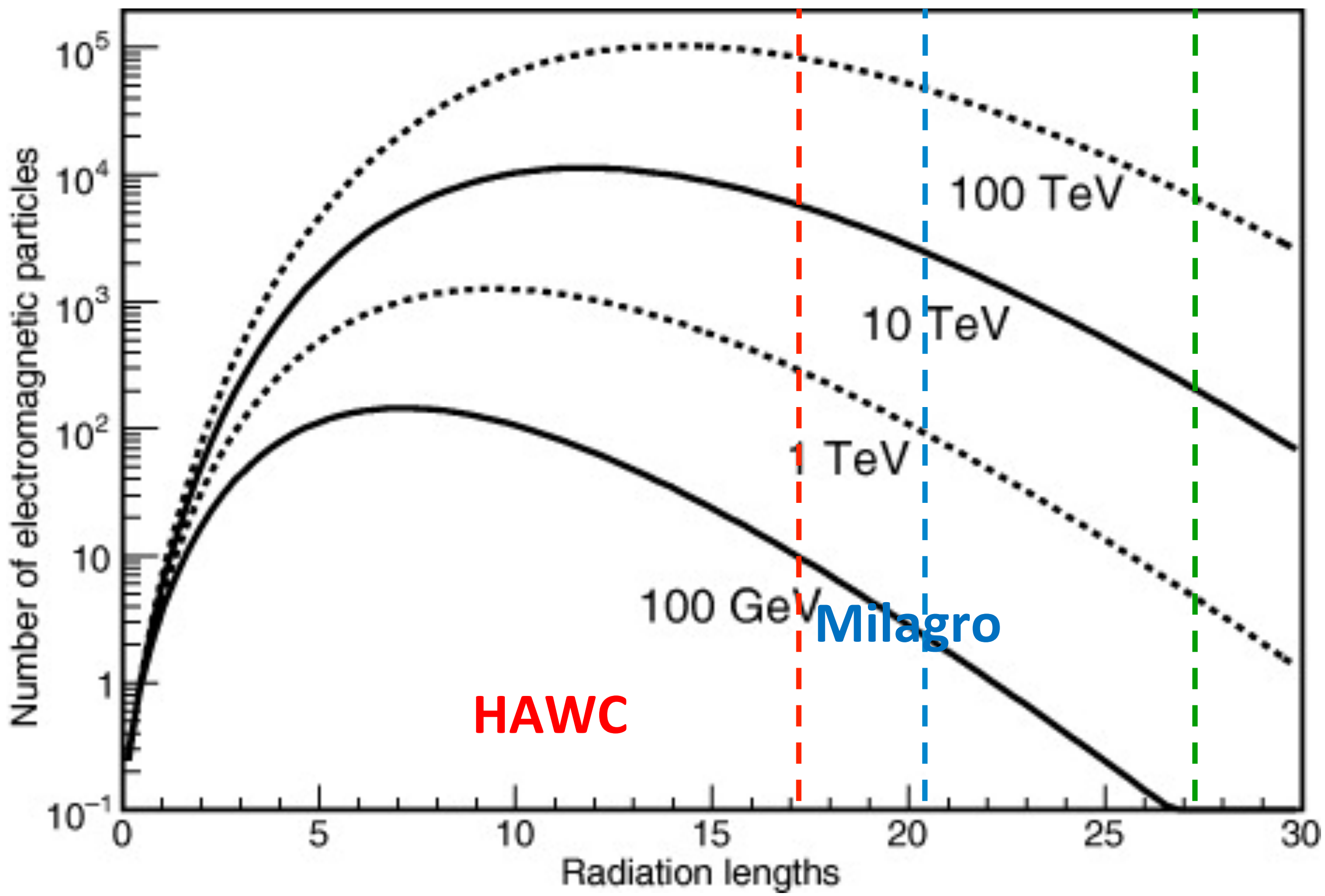
Dark matter: Annihilation/Decay. Sensitive to “dark” Dwarf Galaxies.

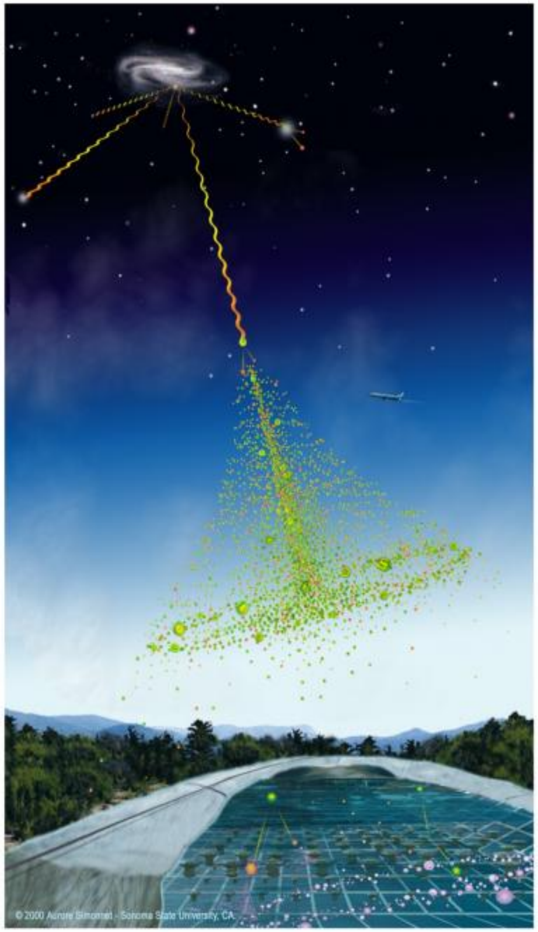




From Milagro to HAWC

- Higher altitude: 2630 m a.s.l. -> 4100 m a.s.l.
- Closer to the shower maximum.





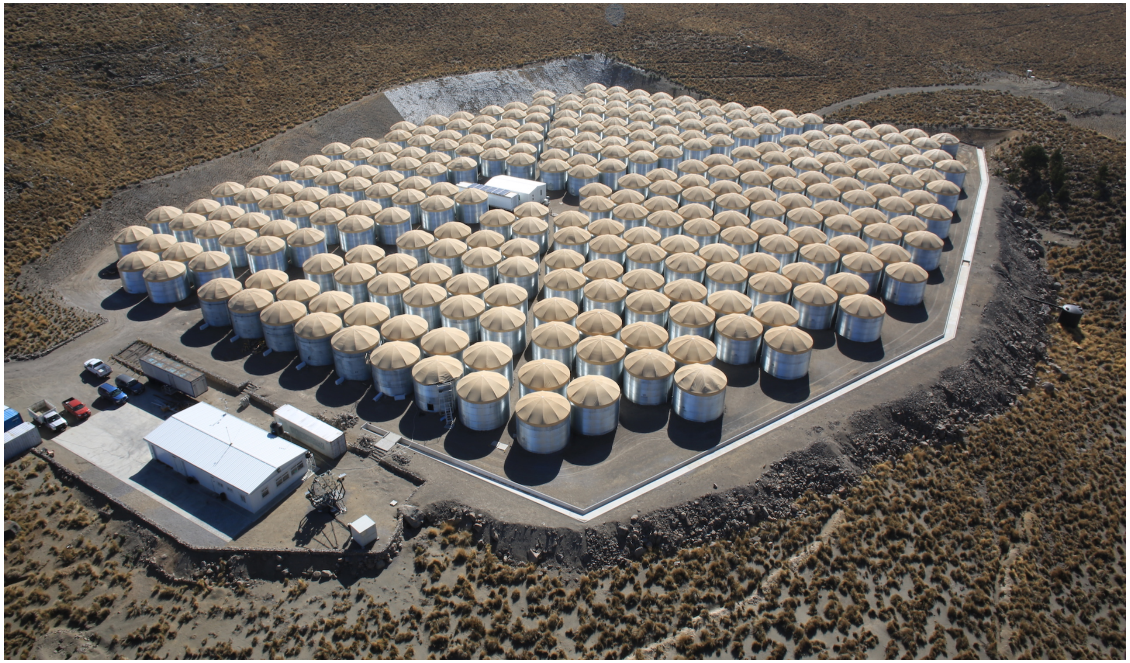
From Milagro to HAWC

- Bigger detector: 4000 m^2 -> 22000 m^2.

Milagro

~60 m x 80 m

HAWC

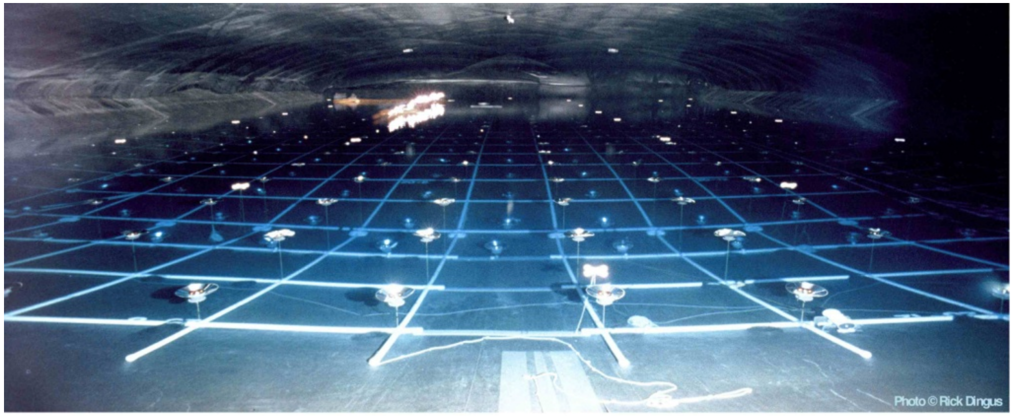


~150 m x 150 m

From Milagro to HAWC

- Improve optical separation:
  one big pond -> individual water Cherenkov detectors (a.k.a. tanks)
- Taking data even during construction.

Milagro



HAWC

Gamma-Ray Flux Less Than Neutrino Flux

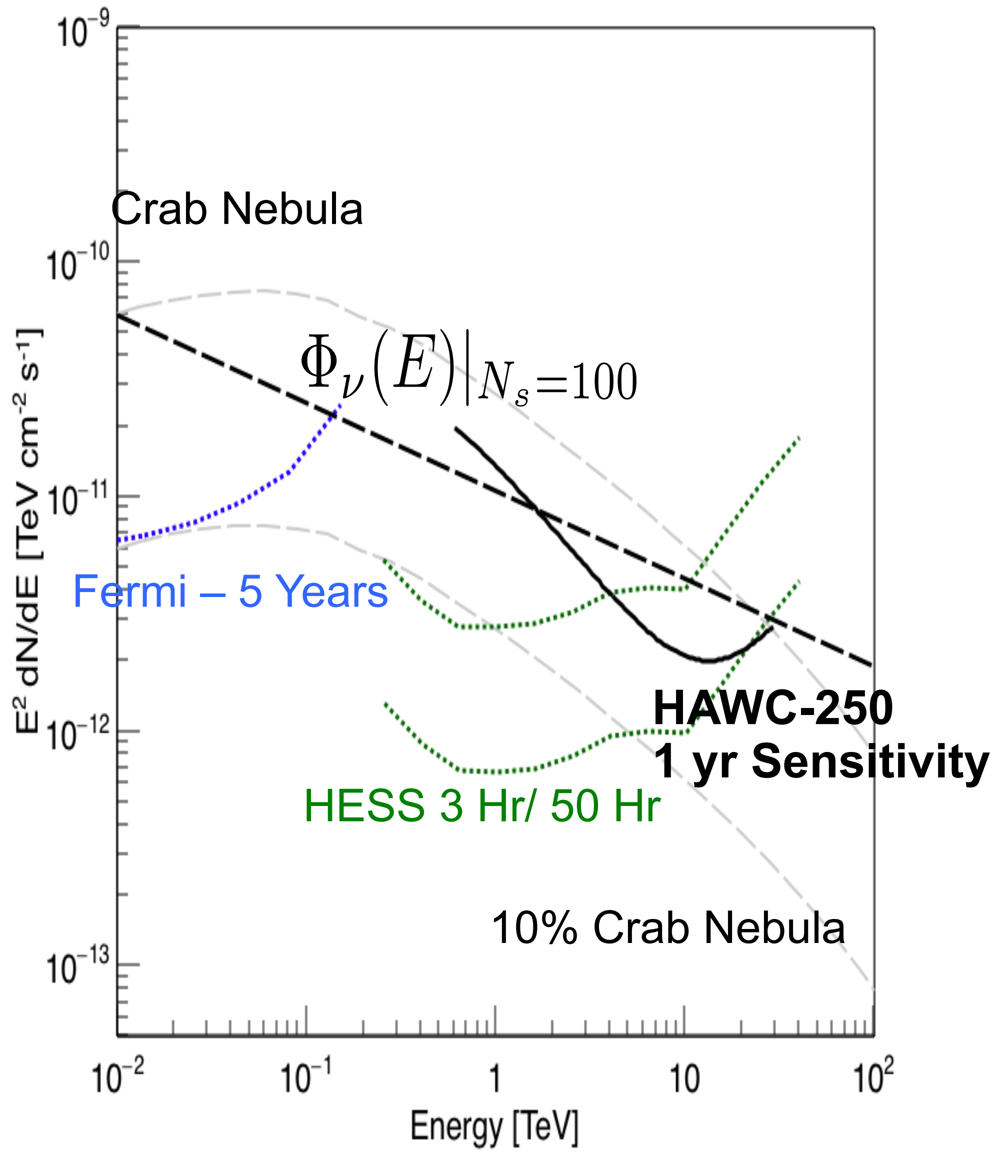
Steady Neutrino Flux assuming it is evenly divided among N_s sources (IceCube, PRL 2014):

$$E^2\Phi_\nu(E) = \frac{4\pi}{N_s} 1.5 \times 10^{-11} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.3} \mathrm{TeV/cm^2\ s}$$

Detectable in HAWC in a year.

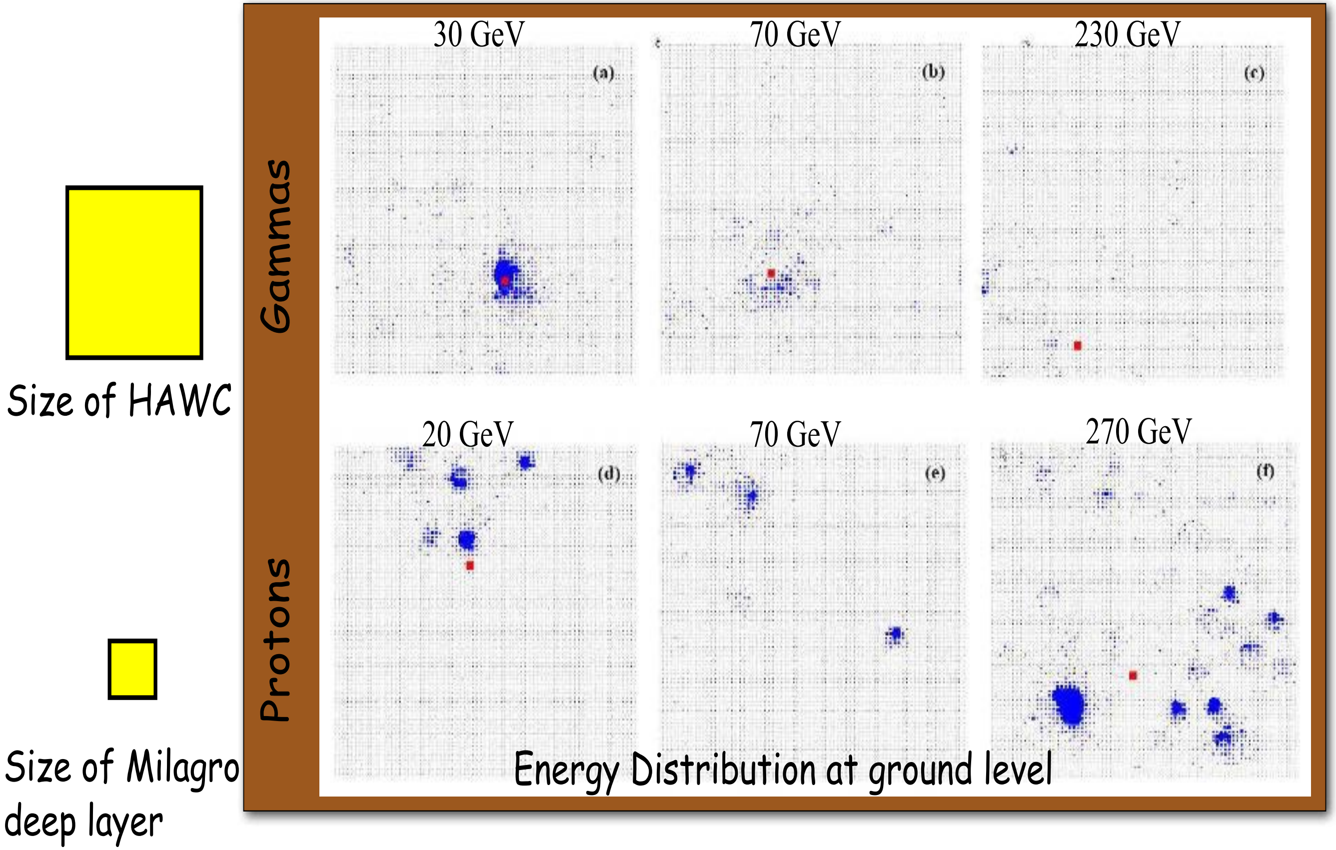
- If photons are not attenuated (i.e. nearby).
- Limits on every IceCube event in our FOV.

HAWC limits are relevant and constraining…



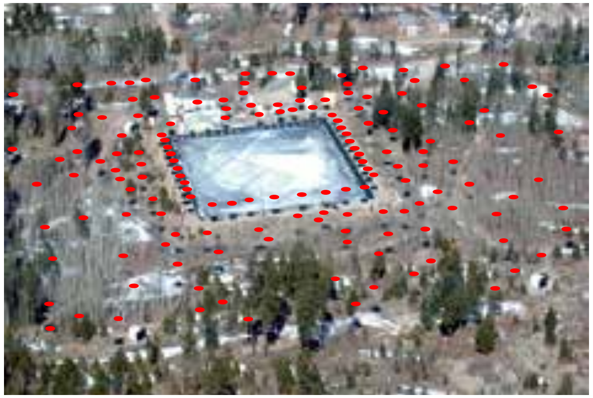
Gamma/Hadron Separation

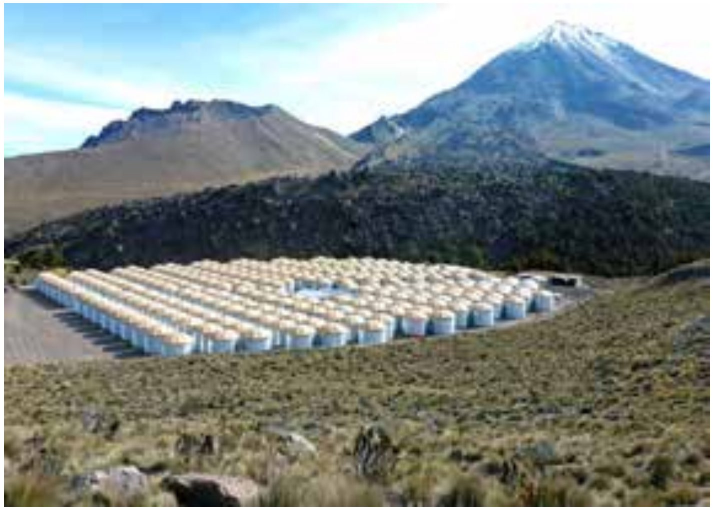
Rejection factor ~ $e^{-<\mu>}$



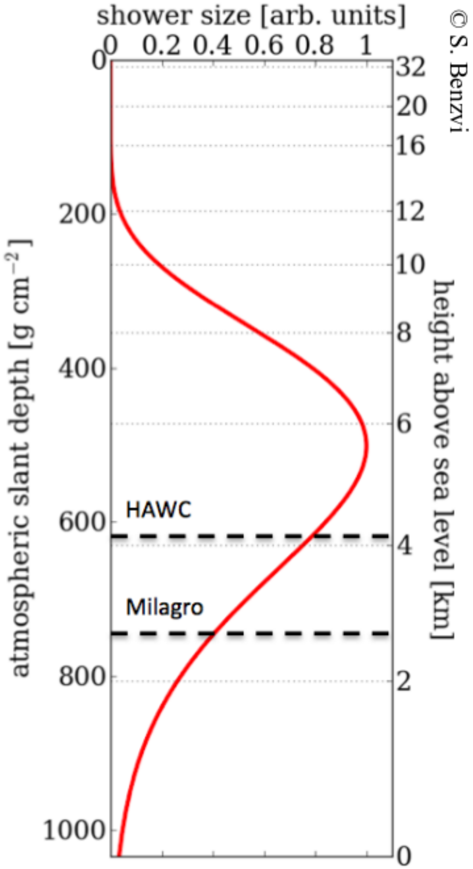
Milagro/Fermi/HAWC Comparison

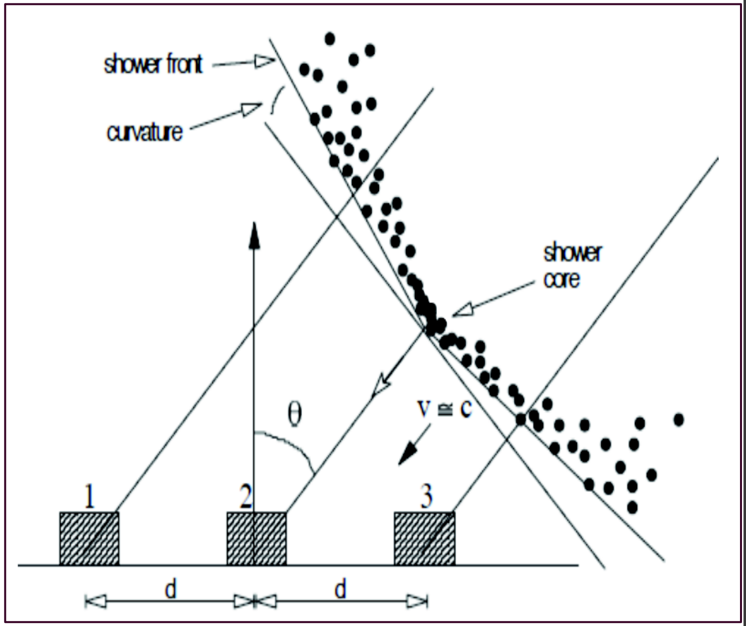
- HAWC is ~15x more sensitive (sig/√bg) than Milagro
  - HAWC sees the Crab at ~6σ in a day - Milagro took 6 months to see 6σ
- Taking into account the Fermi exposure and signal vs Milagro we find that for galactic sources Fermi is ~15x more sensitive than Milagro.
- HAWC at TeV has approximately the same sensitivity as Fermi has at GeV for galactic sources.





Detection Technique of the EAS Arrays





- In HAWC the particle detectors are tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

HAWC Water Cherenkov Detector

- The WCDs are filled with 200,000 l of purified water. The particles from the shower induce **Cherenkov** light in **water,** detected by the 4 PMTs.

Steel frame construction

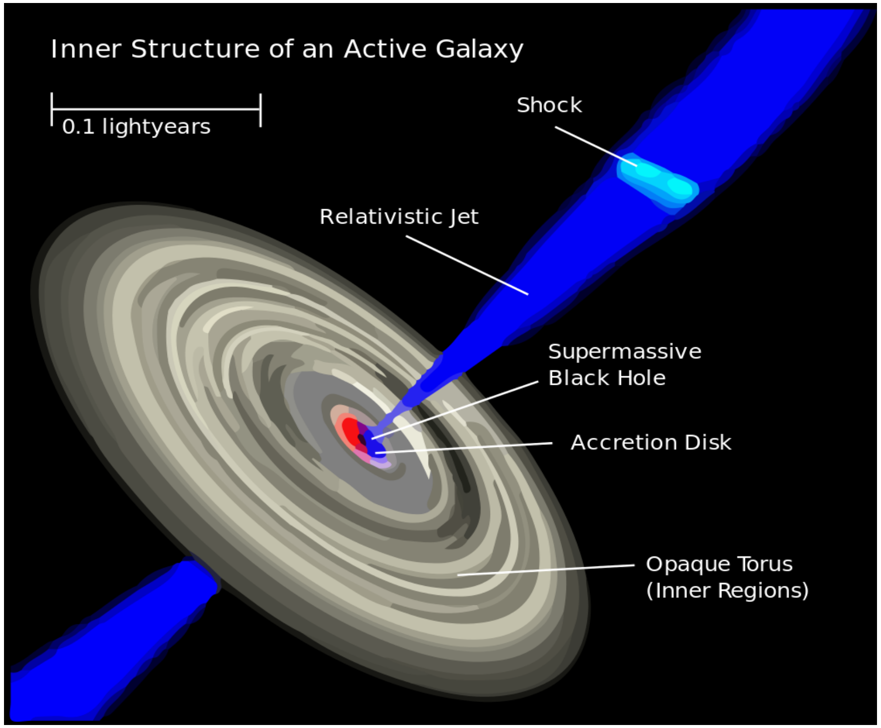
Large plastic bag container

Water trucks filling the tanks

8-inch 10-inch PMTs

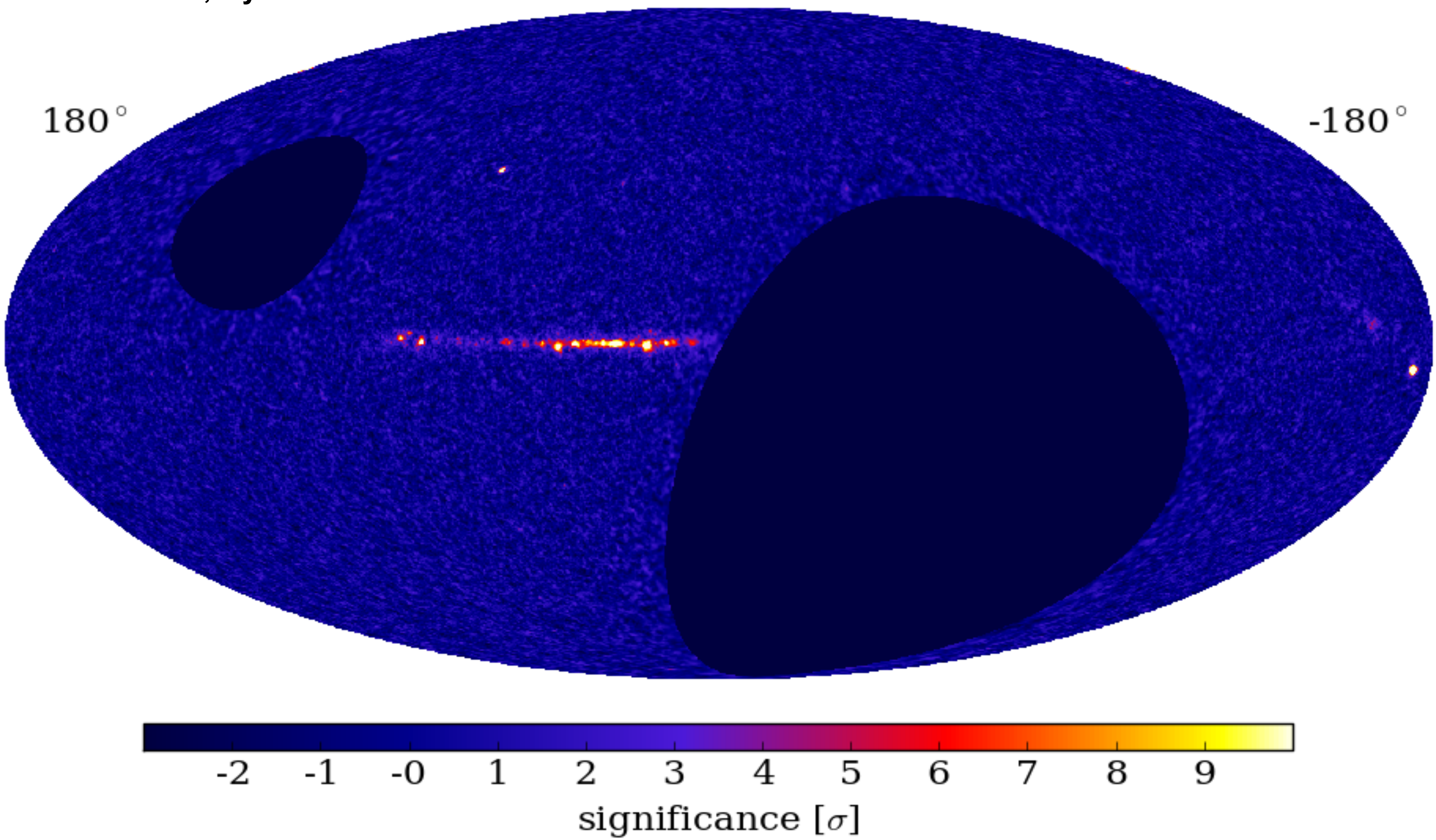
Active Galaxy Markarian 421 flare

early HAWC data



HAWC Gamma-Ray Sky

HAWC 0.1—100 TeV, 1 year



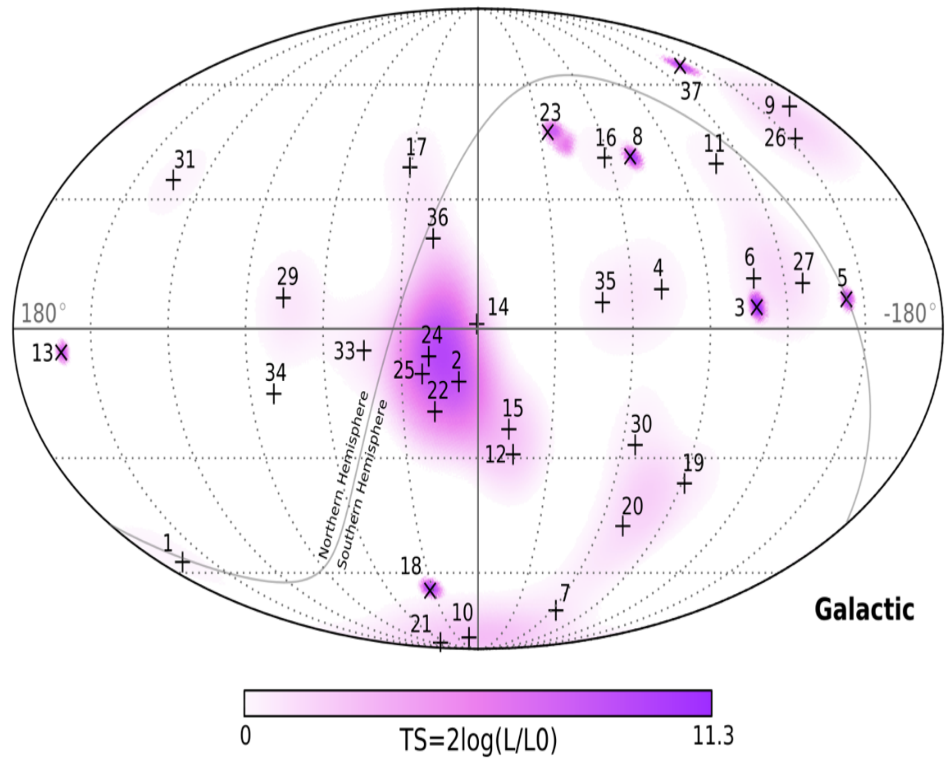
HAWC and Neutrino Telescopes Multi-Messenger Complementarity

Neutrino / Photon Connection: Pions

$$\pi^0 \to \gamma\gamma$$

$$\pi^{\pm} \to \mu\ \nu_\mu \to \nu_\mu\ \nu_\mu\ \nu_e$$

$$\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE}$$



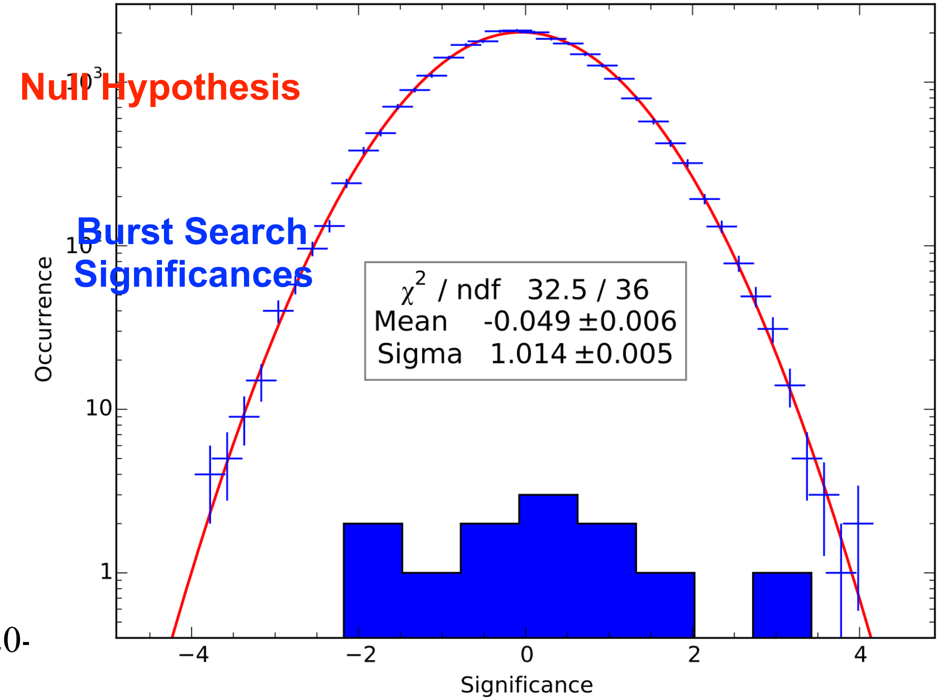
HAWC's Strengths for IceCube Followup

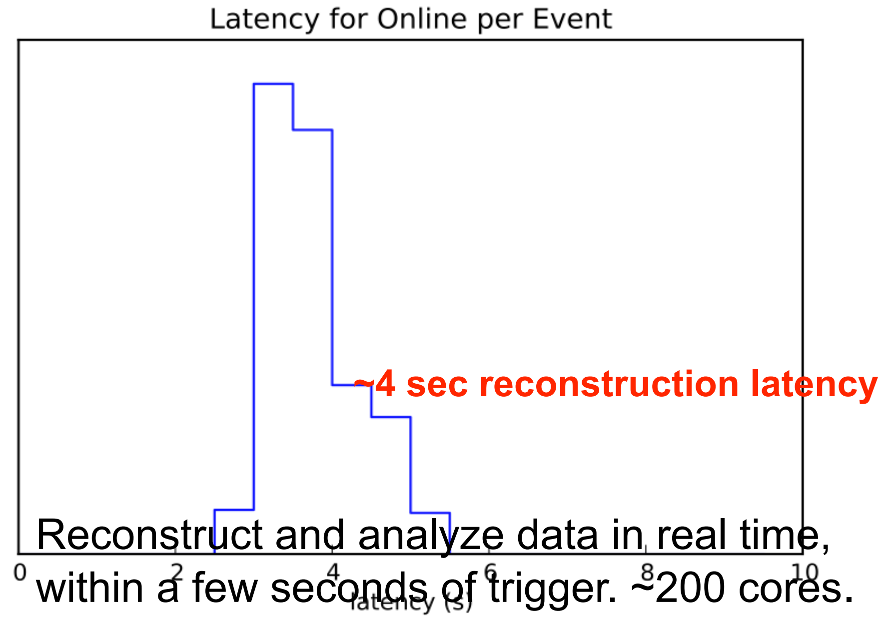
- Wide FOV: Search for cascade coincidences.
- Continuous observation.
- Can search archival data.
- HAWC Sensitive up to 100 TeV

IceCube Collab. Science, 2013; PRL, 2014; Phy.s Rev. D, 2015

Gamma-Ray Burst

- Currently 2 search methods:
  - Follow-up on alerts from satellites (mostly Fermi-GBM).
  - Online search for GRBs. The plan is to deliver transient alerts in near-real time.
- Tested 18 GRBs from Swift. No detection yet.
- Expect 1-2 GRBs per year in HAWC (extrapolating from Fermi) **NIMA 742, 2014, 276-277**.





Reconstruct and analyze data in real time, within a few seconds of trigger. ~200 cores.